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A METALLURGICAL INVESTIGATION OF A LARGE FORGED DISC OF LOW-CARBON N-155 ALLOY

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NACA

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A METALLURGICAL INVESTIGATION OF A LARGE FORGED DISC OF LOW-CARBON N155 ALLOY

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Summary

During the course of a research investigation on the development of heat-resisting alloys for use in turbosupercharger and gas turbine applications, it has been found that the properties of promising alloys are dependent to a large extent on the conditions of fabrication. Because the large size of certain gas-turbine rotors introduced fabrication procedures for which information was not available, a research program is in progress to ascertain the properties of the better alloys in the form of the large forgings required.

The properties of a large disc of Low-Carbon N155 alloy in the hot-forged and stress-relieved condition have been determined by means of stress-rupture and creep tests for time periods up to 2000 hours at 1200°, 1350°, and 1500° F. Short-time tensile test, impact test, and time-total deformation characteristics are included. The results shown are not to be taken as representative of all as-forged discs of this alloy because further data being obtained on other discs indicate that certain variations in properties may be expected.

The following principal results were obtained from the 21-inch-diameter by 3¼-inch-thick disc:

A. Brinell Hardness Range

on surface at rim	260
in middle at center	190

B. Offset Yield Strengths

	(psi)
0.02% offset yield strength at room temperature	58,750
0.2% offset yield strength at:	
room temperature	72,650
1200° F	49,750
1350° F	44,500
1500° F	34,025

C. Rupture-Test Characteristics

	Stress to cause rupture in indicated time periods (psi) (10 hr)	(100 hr)	(1000 hr)
1200° F rupture strength	65,000	55,000	42,000
1350° F rupture strength	40,000	31,000	24,000
1500° F rupture strength	27,300	20,000	14,200

The elongation and reduction of area of the fractured rupture-test specimens were erratic; but the trend was for them to decrease with time for rupture at 1350° and 1500° F.

D. Total Deformation Characteristics under Stress

Total deformation (percent)	Temperature (°F)	Stress for total deformation in indicated time periods (psi) (10 hr)	(100 hr)	(1000 hr)
0.1	1200	20,000	17,500	14,500
.2	1200	31,500	28,000	24,000
.5	1200	39,500	35,000	30,000
1.0	1200	45,500	40,000	35,000
Transition	1200	------	51,500	39,500
0.1	1350	13,800	11,000	8,000
.2	1350	21,400	16,700	12,000
.5	1350	26,500	22,000	17,200
1.0	1350	------	25,000	19,500
Transition	1350	------	24,000	18,000
0.1	1500	11,500	7,700	5,300
.2	1500	16,800	11,000	6,800
.5	1500	------	15,500	10,500
1.0	1500	------	17,400	12,000
Transition	1500	------	16,400	11,200

E. Uniformity

The properties of the disc were quite uniform considering the size of the forging and the characteristics of the alloy.

F. Stability

The impact strength and ductility decreased after creep testing, with the greatest change in the 1350° and 1500° F specimens. The strength values from tensile tests after creep testing did not change appreciably from that of the original material.

The properties of the large forged disc were similar to those obtained from hot-rolled bar stock on the basis of rupture strengths and total deformation characteristics at 1200°, 1350°, and 1500° F. The tensile properties were somewhat lower in accordance with the lower hardness of the large disc.

Comparison of the properties of the Low-Carbon N155 alloy disc with those of a 19-9 DL alloy disc produced by a similar technique showed consistently higher properties at room temperature, 1200°, and 1350° F for the Low-Carbon N155 disc. Comparison at 1500° F was not possible because the 19-9 DL disc had not been tested at this temperature.

INTRODUCTION

This report presents the results of a study of the room temperature, 1200°, 1350°, and 1500° F properties of a large forged disc of Low-Carbon N155 alloy. The primary purpose was to determine the level of properties exhibited by this alloy in the form of large forgings of the type required for rotor wheels in gas turbines. Data from bar stock had shown the alloy to have about the best combination of properties known for wrought materials. (See reference 4.)

The disc investigated for this report is one of several which are being studied for the same purpose, and the report is the second in a series of reports on such discs. The results obtained from an investigation of a large forged disc of 19-9 DL alloy in the as-forged and stress-relieved condition are given in reference 1.

This work is being carried out as part of two correlated programs of research on alloys for gas-turbine applications in progress in this country. The National Advisory Committee for Aeronautics is sponsoring work directed toward the development of improved high-temperature alloys for gas turbines used in aircraft power plants. A concurrent program (project NRC-8) under the auspices of the War Metallurgy Committee, Division 18 of the War Metallurgy Committee of the National Defense Research Committee, Office of Scientific Research and Development, is being directed to the development of alloys for gas-turbine applications in general, and in particular to both ship and aircraft propulsion. The work reported herein was performed with the financial assistance of these two organizations.

A high degree of cooperation has existed between the two programs and between interested alloy producers and gas-turbine manufacturers. This report is based on the joint effort of the two research programs and is being distributed by both the NACA and the OSRD. The investigation of the disc for the NACA was conducted at the Department of Engineering Research of the University of Michigan and for OSRD by the 12 cooperating laboratories of Project NRC-8.

TEST MATERIAL

The available information concerning the disc may be summarized as follows:

Manufacturer:

The Universal-Cyclops Steel Corporation, Titusville, Pa.

Heat number:

A-11534

Chemical composition:

The chemical composition was reported to be the following percentages by the manufacturer:

C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	N_2
0.15	1.74	0.37	21.66	19.40	19.02	2.76	1.90	0.79	0.14

Fabrication procedure:

A 9-inch billet from a 10,000-pound arc-furnace heat was direct-upset to produce a disc 21 inches in diameter by $3^1/_4$ inches in thickness. The finishing temperature for this operation was 1630° F.

Heat treatment:

The as-forged disc was stress-relieved by heating to 1200° F for 2 hours and cooling in air.

Sampling:

The NRC-8 alloy code number assigned to the disc was NR-66D. Figure 1 shows the location of the samples cut from the disc and the code system identifying the coupons. The letters X, Y, and Z refer to the location of the test coupons in respect to the flat faces of the disc. The coupons marked X and Z were taken from the outside thirds of the forging; the Y coupons were taken from the center third of the forging.

EXPERIMENTAL PROCEDURE

The investigation was designed to provide three types of information: (1) the physical properties at room temperature, 1200°, 1350°, and 1500° F which can be expected in large forgings of the Low-Carbon N155 analysis; (2) the variation in properties which might be present in various locations in such large forgings; and (3) the change in properties resulting from exposure to elevated temperatures under stress for prolonged time periods.

The physical-property data obtained for this particular large forged disc of Low-Carbon N155 alloy included short-time tensile properties, impact strengths, rupture-test characteristics, and curves of stress versus time for total deformations of 0.1, 0.2, 0.5, and 1.0 percent at 1200°, 1350°, and 1500° F. The time-deformation data were obtained from time-elongation curves for creep and rupture tests.

The uniformity of the disc material was checked by means of a hardness survey and by tensile and rupture tests on coupons from representative locations throughout the disc. Hardness, tensile, and impact tests and metallographic examinations on specimens after completion of the tests were used to estimate the stability of the material during prolonged exposure to temperature and stress.

The testing procedures used for the short-time tension, stress-rupture, and creep tests were in accordance with the provisions of the A.S.T.M. Recommended Practices E21-43 and E22-41.

RESULTS

The data obtained are compiled as a series of tables and figures with the principal results summarized as figure 2. The source of the data (NACA or NRC-8) is indicated in the tables.

Hardness Survey

The Brinell hardness of material cut from the disc varied between about 190 and 260. (See table I and fig. 3.) The interior of the disc near the center was softest. The hardness increased from the center toward the rim of the disc and also from the interior to the surfaces exposed to the forging hammer. The hardness variations seem small, considering the size of the disc and the known susceptibility of the alloy to work-hardening.

No information is available as to how closely the hardness of this disc could be duplicated in another disc, but it is expected that appreciable differences could result from variations in the forging conditions.

Short-Time Tensile Properties

The results of the short-time tensile tests at room temperature, 1200°, 1350°, and 1500° F are shown in table I, and the stress-strain curves are included as figure 4.

The properties of radial bars taken near the rim were similar, whether from the interior or the surface of the disc. Tangential bars had somewhat higher yield and tensile strengths than radial bars. Sufficient specimens were not available for a survey of uniformity of tensile properties at elevated temperatures.

Charpy Impact Strength

Charpy impact resistance was determined on specimens of the disc material from segment H located about midway between the center and the rim of the disc as shown in figure 1. Data are shown in table II from tests at room temperature, 1200°, 1350°, and 1500° F after holding at temperature for a time period sufficiently long to insure a uniform temperature in the specimens.

The Charpy impact resistance of material from the surface of the disc was a little greater at room temperature than for material taken from the interior of the disc. The values averaged 62 foot-pounds for surface material and 52 foot-pounds for interior material. The tests at high temperatures did not show a significant change in impact resistance as compared with the values at room temperature.

Rupture Test Characteristics

The stress-rupture data for the tests at 1200°, 1350°, and 1500° F are summarized as table III. The rupture strengths were obtained from the curves of stress-rupture time data in figure 5.

Radial specimens from the rim of the center plane of the disc had rupture strengths at 1200° F of 55,000 and 42,000 psi for rupture in 100 and 1000 hours, respectively. In tests at 55,000 psi, tangential bars showed double the rupture time shown by two of the radial bars, but less time than a third radial bar. The slope of the stress-rupture time curve at 1200° F changed at about 100 hours.

The rupture strengths found at 1350° F for radial specimens from the center third of the disc were 31,000 and 24,000 psi for rupture in 100 and 1000 hours. Radial and tangential specimens showed similar rupture properties in tests at 31,000 psi. There was no indication of a break in the slope of the stress-rupture time curve at this temperature. The data were somewhat erratic, especially from the test at 20,000 psi for which the rupture time seemed to be abnormally low.

A lower rupture time was obtained from a bar taken at the center of the disc as compared with rim material at both 1200° and 1350° F.

Tangential specimens taken at the rim of the disc had rupture strengths at 1500° F of 20,000 and 14,200 psi for rupture in 100 and 1000 hours, respectively. No break occurred in the stress-rupture time curve.

The slope of the stress-rupture time curves increased with temperature of testing. The ductility data from the fractured specimens were erratic, with a tendency to decrease in the longer duration test specimens at 1350° and 1500° F. The lowest values were shown by the 1350° F specimens.

Time-Deformation Characteristics

A convenient method of describing the high-temperature strength of a material is by curves of stress versus the time required for various total deformations. Such information with the stress-rupture time curves gives design engineers a complete picture of the expected performance of an alloy under conditions of constant-tension stress. This information is incorporated in figures 6, 7, and 8 for deformations of 0.1, 0.2, 0.5, and 1.0 percent at 1200°, 1350°, and 1500° F for time periods up to 2000 hours. Additional curves showing the time of transition from a minimum creep rate to the increasing rate of third-stage creep have been added so as to show when rapid elongation to failure starts.

The stress-time for total deformation curves were plotted from the data in tables IV, V, and VI. The data were taken from the time-elongation curves of figures 9 through 14 for the creep and rupture tests. Values for total deformations of 2 and 5 percent from the rupture tests were also tabulated. The stress-time for total deformation curves define the stresses to cause the various total deformations in definite time periods of 1, 10, 100, 1000, and 2000 hours. Because these "deformation strengths" are useful numerical ratings of the deformation characteristics, they have been added to tables IV, V, and VI.

Creep Strengths

Many engineers are accustomed to base designs on creep rates, especially for long periods of service. For this reason the creep-rate data have been collected from the time-elongation curves as table VII, and the logarithmic stress-creep rate curves are shown as figure 15. The creep rates used were either minimum rates or final rates from 1000 hour tests at 1200° F and 2000 hour tests at 1350° and 1500° F. The creep strengths obtained from figure 15 were:

Temperature (°F)	Stress for indicated creep rates (psi)	
	0.0001 percent/hr	0.00001 percent/hr
1200	28,000	15,000
1350	16,000	7,900
1500	8,700	5,000 (estimated)

These creep strengths are compared with the deformation strengths in tables IV, V, and VI. The creep strength for a rate of 0.0001 percent per hour at 1200° F is apparently safe to use for time periods up to about 10,000 hours. Extrapolation of the transition curve of figure 6 indicates that third-stage creep will not occur at 28,000 psi until about 10,000 hours. At 1350° and 1500° F extrapolation of the transition curves of figures 7 and 8 indicates that increasing creep rates are to be expected after only 2000 hours under stresses corresponding to the creep strengths for a rate of 0.0001 percent per hour. The slower creep-rate strengths probably can be used for much longer time periods.

Stability Characteristics

Some of the test specimens were subjected to tensile, impact, and hardness tests at room temperature after creep testing at 1200°, 1350°, and 1500° F, with the results shown in table VIII. The decrease in impact strength and increase in hardness were the most significant changes. The tensile test on a specimen creep tested at 1500° F indicates that 2000 hours at this temperature under stress reduces the room-temperature tensile strength values to an appreciable extent.

The yield strengths of specimen 21Y were abnormally high after creep testing at 1200° F. This may have been caused by work hardening and precipitation which accompanied the total deformation of 0.63 percent during creep testing, or may simply have been due to variation between specimens. The tensile properties of specimen 19X, which deformed only 0.11 percent during creep testing, were similar to the original material. Such a trend of effect of deformation at 1200° F is somewhat substantiated by the lowered impact resistance and increased hardness for specimen 19Y, which deformed 1.5 percent, as compared to specimen 21X which deformed only 0.245 percent.

For the specimens tested in creep at 1350° F, no significant effects on proportional limits, yield and tensile strengths were noted, regardless of the testing conditions and total deformations that occurred. However, elongation, reduction of area, and impact resistance were significantly reduced, accompanied by an increase in hardness.

In general, the microstructure of the forged disc was quite uniform. The grain size range was 3 to 6, with different sizes predominating in the various samples examined, as shown in figures 16 through 20. The appearance of bands of excess constituents depended on the relation of the plane of the sample to the direction and degree of flow of the metal during forging. Extremes of structure observed at the center and the rim of the disc are shown in figure 16.

The photomicrographs of figure 17 show that testing at 1200° F tended to make the grain boundary precipitation more complete. Fractures in stress-rupture tests at 1200° F were largely transcrystalline but, as shown in figure 18, some intergranular cracking was observed adjacent to the fracture.

Figures 18, 19, and 20 show a heavy, general precipitation as a result of tests of about 2000 hours at 1350° F. It has been shown that this significant change in structure produced little change in tensile properties at room temperature, but did cause a considerable reduction in ductility and impact resistance.

Figure 20 also shows the microstructure after a creep test of 2000 hours at 1500° F. When compared with the structures resulting from creep tests at 1350° F, it appears that some agglomeration of the precipitate has occurred, which would account for the lowered residual room-temperature tensile properties.

DISCUSSION OF RESULTS

The tensile, rupture, and time-deformation data provide as nearly complete design information for this Low-Carbon N155 disc as can be obtained in the laboratory from tests under constant-tensile stresses. The test data contained in this report apply only to this particular forged disc. Experience indicates that the properties depend on the particular manufacturing procedure used in the production of the discs. Until checked by experiment, it should not be assumed that the high level of properties herein reported apply either to a forged disc fabricated by a different producer or to a similar disc fabricated by the same producer using similar forging techniques.

The properties found for this disc were remarkably good, both on the basis of the magnitude of the values found and in comparison to those which have been obtained for bar stock, as is shown by comparative values for hot-worked bar stock in table IX. Lower hardness and room-temperature and 1200° F short-time tension properties were obtained on the large forged disc than on hot-rolled bar stock, probably as a result of a smaller amount of reduction at the lower temperatures during forging. The considerable differences between disc and bar stock shown in short-time tests were largely absent in long-time rupture tests. At 1200° F the rupture properties of the disc were only slightly lower than for hot-worked bar stock, and at 1350° and 1500° F were very similar to those for bar stock.

The total deformation characteristics and creep strengths at 1500° F for the large forged disc were similar to those for the one heat of as-rolled bar stock for which data were available. At 1200° and 1350° F, comparative data from creep tests are not available.

Similar data to those obtained in this investigation have previously been published in reference 1 for a 19-9 DL alloy disc of the same size and processed in a similar manner by the same alloy producer. The comparative data for the discs of the two alloys are shown in table X. The two discs were finish-forged at about the same temperature. The more highly alloyed Low-Carbon N155 disc showed consistently higher properties at room temperature, 1200° and 1350° F than did the 19-9 DL disc. Comparative data are not available at 1500° F because the 19-9 DL disc was not tested at this temperature.

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TABLE I

SHORT-TIME TENSILE PROPERTIES FOR THE LOW-CARBON N155 ALLOY FORGED DISC

Specimen number	Specimen location	Temperature (°F)	Tensile strength (psi)	Offset yield strength (psi)			Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Brinell hardness	Modulus of elasticity E x 10^6
				(0.02%)	(0.1%)	(0.2%)					
(1) DY1	CRR	Room	117,600	58,000	67,000	71,500	47,500	30	48.1	211	30.8
(1) DY2	CRR	----do-----	119,500	58,000	69,000	73,500	45,000	32	52.2	211	29.8
(2) 18Z	SRR	----do-----	118,300	------	------	-------	------------	37.3	56.2	-------	----------
(2) 19Z	SRR	----do-----	117,050	60,000	66,600	69,600	51,400	41.7	56.2	-------	28.1
18X	SRR	----do-----	119,000	59,000	73,000	76,000	42,500	36	54.7	255	30.2
(1) 5Y	CTR	----do-----	127,300	68,000	80,500	87,500	50,000	32.5	48.4	251	29.5
5X	STR	----do-----	123,750	64,000	78,000	83,000	45,000	32	48.4	239	30.2
(1) FBY1	CRR	1200	83,000	------	48,000	50,500	30,000	17	33.8	-------	22.0
(1) EBY2	CRR	1200	83,000	------	47,000	49,000	30,000	25	33.4	-------	22.5
(1) 20Y	CRR	1350	59,750	------	37,500	40,250	22,500	24	24.8	-------	20.5
(1) EBX	SRR	1350	60,500	------	46,500	49,000	27,500	24.5	31.2	-------	20.5
(2) 17X	SRC	1500	41,450	------	33,500	34,700	24,250	28	29.8	-------	22.0
(2) 17Y	CRC	1500	39,400	------	32,100	33,350	23,000	33	27.8	-------	16.0

(1) NACA data.
(2) NRC-8 data.
CRR center plane radial specimen at rim of disc.
SRR surface plane radial specimen at rim of disc.
CTR center plane tangential specimen at rim of disc.
STR surface plane tangential specimen at rim of disc.
SRC surface plane radial specimen at center of disc.
CRC center plane radial specimen at center of disc.

TABLE II

CHARPY NOTCHED-BAR IMPACT RESISTANCE AT ROOM TEMPERATURE, 1200°, 1350°, AND 1500° F FOR THE LOW-CARBON N155 ALLOY FORGED DISC

Specimen number	Location of test material in disc	Temperature of test (°F)	Charpy impact strength (ft-lb)
H1A	Surface	Room	64
H2A		----do-----	55
H3A		----do-----	67
H1C	Interior	Room	50
H2C		----do-----	60
H3C		----do-----	45
H1B		1200	47
H1D		1200	50
H2B		1200	57
H2D		1350	54
H3B		1350	49
H3D		1350	47
H4B		1500	47
H4D		1500	46
H5B		1500	45

0.394-in.-square specimens with a 0.079-in.-deep V-notch.

For location of the test specimens in the forged disc, see the diagram in figure 1.

Specimens held at temperature until heated through (approx. 1 hr).

All data from NRC-8 tests.

TABLE III

1200°, 1350°, AND 1500° F RUPTURE-TEST CHARACTERISTICS OF THE

LOW-CARBON N155 ALLOY FORGED DISC

Specimen number	Specimen location	Temperature (°F)	Stress (psi)	Rupture time (hr)	Elongation in 1 in. (percent)	Reduction of area (percent)
(1) DY	CRR	1200	77,000	1.07	9	16.0
(1) DY	CRR	1200	72,000	2.35	26	21.8
(1) EY	CRR	1200	55,000	94.	12	10.9
(1) EY	CRR	1200	50,000	204.	10	9.7
(1) EY	CRR	1200	45,000	502.	7	8.5
(1) EY	CRR	1200	40,000	1461.	12	16.7
(2) 22Y2	CRR	1200	50,000	175.5	11.6	13.2
(2) C2	----------	1200	50,000	117.2	9.2	10.1
(1) DX	SRR	1200	55,000	32.	7	7.3
(1) 18Y	CRC	1200	55,000	28.	13	20.6
(1) 4Y	CTR	1200	55,000	77.5	8	10.2
(1) 4X	STR	1200	55,000	60.	12	16.7
(1) FY	CRR	1350	52,000	1.05	29	33.0
(1) EY	CRR	1350	45,000	4.47	12	16.7
(1) FY	CRR	1350	35,000	36.	23	33.0
(1) FY	CRR	1350	30,000	186.	9	11.5
(1) FY	CRR	1350	25,000	432.	10	19.5
(1) 20Y	CRR	1350	25,000	738.5	7	9.1
(1) EY	CRR	1350	23,000	1734.	5	6.2
(1) FY	CRR	1350	20,000	1336.	5	6.0
(1) DX	SRR	1350	31,000	148.5	23	31.9
(1) 18Y	CRC	1350	31,000	68.5	18	21.2
(1) 4Y	CTR	1350	31,000	158.	14	19.5
(1) 4X	STR	1350	31,000	121.5	24	31.4
(2) 1X	STR	1500	30,000	4.5	25.8	37.6
(2) 4Z	STR	1500	20,000	107.5	7.5	16.6
(2) 7Z	STR	1500	18,000	215.	24.0	18.8
(2) 5Z	STR	1500	16,000	530.8	9.5	12.6
(2) 7Y	CTR	1500	13,000	1514-1558	10.0	17.0

Rupture Strengths

Temperature (°F)	Stress for rupture in indicated time periods (psi)				
	(1 hr)	(10 hr)	(100 hr)	(1000 hr)	(2000 hr)
1200	77,000	65,000	55,000	42,000	38,500
1350	52,000	40,000	31,000	24,000	22,500
1500	----------	[3]27,300	20,000	14,200	12,500

(1) NACA data. (Specimens were 0.160 in. in diameter with a gage length of 1 in.)

(2) NRC-8 data. (Specimens were 0.505 in. in diameter with a gage length of 2 in.)

[3]Estimated.

CRR center plane radial specimen at rim of disc.
SRR surface plane radial specimen at rim of disc.
CRC center plane radial specimen at center of disc.
CTR center plane tangential specimen at rim of disc.
STR surface plane tangential specimen at rim of disc.

TABLE IV

STRESS-TIME FOR TOTAL DEFORMATION DATA AT 1200° F FOR THE LOW-CARBON N155 ALLOY FORGED DISC

Specimen number	Stress (psi)	Initial deformation (percent)	Time for indicated total deformation (hr)						Transition to third-stage creep	
			(0.1%)	(0.2%)	(0.5%)	(1%)	(2%)	(5%)	time (hr)	% deformation
EBY-1	15,000	0.070	550	------	------	------	------	------	------	------
19X	17,000	.076	285	------	------	------	------	------	------	------
FBY-2	20,000	.090	6.5	------	------	------	------	------	------	------
21X	25,000	.113	------	435	------	------	------	------	------	------
21Y	30,000	.135	------	27	660	------	------	------	------	------
19Y	35,000	.191	------	.2	118	947	------	------	------	------
EY	40,000	.20	------	------	10	125	645	1290	960	2.6
EY	45,000	.26	------	------	<1	12	150	500	315	2.9
EY	50,000	.48	------	------	------	1.5	40	157	135	4.0
EY	55,000	approx. 1.5	------	------	------	------	5	38	60	6.5

Total deformation (percent)	Stress to cause total deformations in indicated time periods (psi)				
	(1 hr)	(10 hr)	(100 hr)	(1000 hr)	(2000 hr)
0.1	21,500	20,000	17,500	14,500	13,500
.2	34,000	31,500	28,000	24,000	23,000
.5	44,500	39,500	35,000	30,000	28,500
1.0	51,000	45,500	40,000	35,000	33,500
Transition	-----------	------------	51,500	39,500	36,000

Creep strengths (rate taken at 1000 hr)

0.00010 percent per hour = 28,000 psi
0.00001 percent per hour = 15,000 psi

NACA data.

TABLE V

STRESS-TIME FOR TOTAL DEFORMATION DATA AT 1350° F FOR THE LOW-CARBON N155 ALLOY FORGED DISC

	Specimen number	Stress (psi)	Initial deformation (percent)	Time for indicated total deformation (hr)						Transition to third-stage creep	
				(0.1%)	(0.2%)	(0.5%)	(1%)	(2%)	(5%)	time (hr)	% deformation
(1)	23Y	8,000	0.045	1050	------	------	---	-------	------	---	-------
(1)	22Z	10,000	.050	570	[3]3000	------	---	-------	------	---	-------
(1)	22X	12,000	.080	20	790	------	---	-------	------	---	-------
(1)	23X	15,000	.090	5	350	[3]3350	---	-------	------	---	-------
(1)	21Z	17,000	.093	1	100	1200	---	-------	------	---	-------
(1)	16Z	20,000	.110	-------	15	235	838	-------	------	450	0.675
(1)	23Z	25,000	.127	-------	1.4	27	105	-------	------	70	.775
(2)	EY	23,000	.115	-------	------	------	---	670	------	---	-------
(2)	FY-20Y	25,000	.121	-------	------	------	---	148-206	374-650	---	-------
(2)	FY	30,000	.16	-------	------	------	---	74	155	---	-------

Total deformation (percent)	Stress to cause total deformations in indicated time periods (psi)				
	(1 hr)	(10 hr)	(100 hr)	(1000 hr)	(2000 hr)
0.1	17,000	13,800	11,000	8,000	---------
.2	26,000	21,400	16,700	12,000	[3]10,700
.5	--------	26,500	22,000	17,200	[3]15,900
Transition	--------	----------	24,000	18,000	----------
1.0	--------	----------	25,000	19,500	----------

Creep strengths (minimum rates)

0.0001 percent per hour = 16,000 psi
0.00001 percent per hour = 7,900 psi

(1) NRC-8 data.
(2) NACA data.
[3]Estimated.

TABLE VI

STRESS-TIME FOR TOTAL DEFORMATION DATA AT 1500° F FOR THE LOW-CARBON N155 ALLOY FORGED DISC

Specimen number	Stress (psi)	Initial deformation (percent)	Time for indicated total deformation (hr) (0.1%)	(0.2%)	(0.5%)	(1%)	(2%)	(5%)	Transition to third-stage creep: time (hr)	% deformation
16Y	7,000	0.028	170	840	-------	------	-----	------	------	--------
7X	10,000	.063	20	160	1430	------	-----	-------	1800	0.575
7Y	13,000	.075	5	50	275	630	1040	1400	600	.94
5Z	16,000	.097	1	13	84	200	320	480	114	.60
7Z	18,000	.12	--------	7	36	70	112	160	45	.60
4Z	20,000	.12	--------	3	18	38	65	-------	20	.53

Total deformation (percent)	Stress to cause total deformations in indicated time periods (psi) (1 hr)	(10 hr)	(100 hr)	(1000 hr)	(2000 hr)
0.1	16,000	11,500	7,700	[1]5,300	-------------
.2	-------------	16,800	11,000	6,800	-------------
.5	-------------	-------------	15,500	10,500	[1]9300
Transition	-------------	-------------	16,400	11,200	[1]9700
1.0	-------------	-------------	17,400	[1]12,000	-------------

<u>Creep strengths (minimum rates)</u>

0.0001 percent per hour = 8700 psi
0.00001 percent per hour = [1]5000 psi

NRC-8 data.

[1]Estimated.

TABLE VII

CREEP TEST DATA AT 1200°, 1350°, AND 1500° F FOR THE LOW-CARBON N155 ALLOY FORGED DISC

Specimen number	Temperature (°F)	Stress (psi)	Duration (hr)	Deformation upon application of load (percent)	Creep rate - percent per hour at-				Total deformation - percent at-			
					500 hr	1000 hr	1500 hr	2000 hr	500 hr	1000 hr	1500 hr	2000 hr
(1) EBY-1	1200	15,000	775	0.070	0.00002	[3]0.000010	--------	--------	0.098	--------	--------	--------
(1) 19X	1200	17,000	1055	.076	.000024	.000016	--------	--------	.105	0.114	--------	--------
(1) FBY-2	1200	20,000	815	.090	.000054	[3].00003	--------	--------	.141	[3].153	--------	--------
(1) 21X	1200	25,000	1075	.113	.00010	.000062	--------	--------	.206	.241	--------	--------
(1) 21Y	1200	30,000	1530	.135	.00033	.000150	0.000130	--------	.458	.552	0.620	--------
(1) 19Y	1200	35,000	1060	.191	.00056	.00044	--------	--------	.790	1.023	--------	--------
(2) 23Y	1350	8,000	2016	.045	.000056	.000040	.000025	0.000013	.080	.098	.123	0.130
(2) 22Z	1350	10,000	2040	.050	.000066	.000067	.000032	.000021	.095	.127	.156	.170
(2) 22X	1350	12,000	2000	.080	.000108	.000092	.000049	.000039	.169	.219	.255	.276
(2) 23X	1350	15,000	2000	.090	.000182	.000164	.000091	.000070	.229	.320	.378	.418
(2) 20Z	1350	17,000	2040	.094	.000268	.000242	.000155	.000112	.262	.398	.496	.559
(2) 21Z	1350	17,000	2013	.093	.000243	.000278	.000130	.000120	.307	.450	.561	.622
(2) 16Z	1350	20,000	1030	.110	.000830	.000850	--------	--------	.722	1.146	--------	--------
(2) 16Y	1500	7,000	2000	.028	.000120	.000035	.000090	.000040	.166	.210	.238	[4].312
(2) 7X	1500	10,000	2185	.063	.000375	.000187	.000188	.000200	.323	.422	.513	.623

(1) NACA data.
(2) NRC-8 data.
[3]Final creep rate and total deformation.
[4]Temperature at 1660° F for 4 hr at test time of 1620 hr.

TABLE VIII

EFFECT OF 1200°, 1350°, AND 1500° F CREEP TESTING ON THE ROOM-TEMPERATURE

PHYSICAL PROPERTIES OF THE LOW-CARBON N155 ALLOY FORGED DISC

Specimen number	Prior testing conditions: Temperature (°F)	Stress (psi)	Time (hr)	Residual room-temperature properties: Tensile strength (psi)	Offset yield stress (psi) (0.02%)	(0.1%)	(0.2%)	Proportional limit (psi)	Elongation in 2 in. (percent)	Reduction of area (percent)	Izod impact strength (ft-lb) NRC-8	NACA	Vickers hardness
(1)	Original condition			118,290	58,750	68,900	72,650	46,600	35	54	50,63	30,37	Surface 241-251 Center Rim 223 Center 211-222
(2) 19Y	1200	35,000	1060	--------	-------	------	------	------	---------	---------	-----	11,20	265
21Y	1200	30,000	1532	120,750	75,000	80,000	82,000	60,000	21	27.8	-----	-----	--------------
21X	1200	25,000	1075	--------	-------	------	------	------	---------	---------	-----	19,20	251
19X	1200	17,000	1054	116,750	51,000	65,000	70,500	30,000	30	37.9	-----	-----	--------------
(3) 16Z	1350	20,000	1030	--------	-------	------	------	------	---------	---------	5,4.5	-----	252
21Z	1350	17,000	2013	124,500	58,750	66,000	69,800	50,250	12	13	-----	-----	--------------
23X	1350	15,000	2000	--------	-------	------	------	------	---------	---------	4.5,4	-----	266
22X	1350	12,000	2000	127,000	57,000	65,300	69,500	47,500	15	15	-----	-----	--------------
22Z	1350	10,000	2040	--------	-------	------	------	------	---------	---------	5,4.5	-----	257
23Y	1350	8,000	2016	128,000	54,500	65,300	69,500	42,500	14	14	-----	-----	--------------
7X	1500	10,000	2185	--------	-------	------	------	------	---------	---------	4.5,4.5	-----	236
16Y	1500	7,000	2000	114,000	43,000	50,500	54,500	36,250	15	16	-----	-----	--------------

(1) Average of five tests on center and surface plane radial specimens at rim of disc.
(2) NACA data (0.365-in.-square with a 0.050-in.-deep V-notch impact specimen.)
(3) NRC-8 data (0.450-in.-diam. impact test specimens, V-notch.)

TABLE IX

COMPARATIVE PROPERTIES OF LOW-CARBON N155 ALLOY AS A LARGE FORGED DISC AND AS HOT-WORKED BAR STOCK

	Large disc		Hot-worked bar stock				
Heat number	A-11534		-------	UCC No 1	------	H994 & J67	R3268
References	-----------------		[a]UCC	[b]UCC	2 & 3	4	[c]-----
Chemical composition, percent							
C	0.15		0.13	0.13	0.14	0.10	0.13
Mn	1.74		1.45	1.48	1.48	1.5	1.37
Si	.37		.65	.52	.52	.50	.44
Cr	21.66		21.50	21.3	21.3	20.0	22.80
Ni	19.40		21.01	20.0	20.0	20.0	18.70
Co	19.02		20.50	20.0	20.0	20.0	20.66
Mo	2.76		3.15	3.06	3.06	3.0	3.16
W	1.90		2.20	2.20	2.20	2.0	1.64
Cb	.79		1.05	1.10	1.10	1.0	1.11
N_2	.14		.15	.13	.14	.1	.13
Hot work finishing temperature, °F	1630		-------	------	------	2100-1350	1600
Location of specimens in disc	Radial	Tangential	-------	------	------	-----------	---------
Brinell hardness	211-255	239-251	-------	------	------	268	330
Room-temperature tensile properties							
Tensile strength, psi	118,290	125,520	142,700	------	------	135,620	161,500
0.02% offset yield strength, psi	58,750	66,000	-------	------	------	80,620	116,000
0.1% offset yield strength, psi	68,900	79,250	-------	------	------	-----------	---------
0.2% offset yield strength, psi	72,650	85,250	116,500	------	------	98,950	134,000
Elongation, percent in 2 inches	35	32	16	------	------	32	23
Reduction of area, percent	54	48	45	------	------	52	35
1200° F tensile properties							
Tensile strength, psi	83,000	---------	-------	------	------	89,500-100,500	116,000
0.2% offset yield strength, psi	49,750	---------	-------	------	------	60,800-79,700	---------
Elongation, percent in 2 inches	21	---------	-------	------	------	22-29	13
Reduction of area, percent	33	---------	-------	------	------	31-41	23
1200° F rupture characteristics							
100-hr rupture strength, psi	55,000	---------	-------	60,000	------	58,000	53,000
100-hr rupture elongation, % in 1 inch	12	---------	-------	------	------	14	13
1000-hr rupture strength, psi	42,000	---------	-------	49,000	------	48,000	44,000
1000-hr rupture elongation, % in 1 inch	10	---------	-------	------	------	14	---------

See footnotes at end of table.

TABLE IX.- (CONTINUED)

	Large disc	Hot-worked bar stock				
Heat number	A-11534	------	UCC No 1	------	H994 & J67	R3268
1350° F tensile properties						
Tensile strength, psi	60,125	------	------	------	80,940	------
0.2% offset yield strength, psi	44,500	------	------	------	65,650	------
Elongation, percent in 2 inches	24	------	------	------	24	------
Reduction of area, percent	28	------	------	------	37	------
1350° F rupture characteristics						
100-hr rupture strength, psi	31,000	------	36,000	------	36,000	25,000
100-hr rupture elongation, % in 1 inch	15	------	------	------	11	9
1000-hr rupture strength, psi	24,000	------	27,000	------	27,500	15,000
1000-hr rupture elongation, % in 1 inch	6	------	------	------	<6	------
1500° F rupture characteristics						
100-hr rupture strength, psi	20,000	------	20,000	20,000	------	------
100-hr rupture elongation, % in 1 inch	7.5	------	------	10	------	------
1000-hr rupture strength, psi	14,200	------	14,000	12,500	------	------
1000-hr rupture elongation, % in 1 inch	10	------	------	8	------	------
1500° F time-deformation strengths						
0.1% in 10 hours	11,500	------	------	10,000	------	------
0.1% in 100 hours	[d]7,700	------	------	7,500	------	------
0.1% in 1000 hours	[d]5,300	------	------	------	------	------
0.2% in 10 hours	16,800	------	------	18,500	------	------
0.2% in 100 hours	11,000	------	------	10,400	------	------
0.2% in 1000 hours	6,800	------	------	7,500	------	------
0.5% in 10 hours	------	------	------	------	------	------
0.5% in 100 hours	15,500	------	------	14,500	------	------
0.5% in 1000 hours	10,500	------	------	11,000	------	------
1.0% in 10 hours	------	------	------	------	------	------
1.0% in 100 hours	[d]17,400	------	------	17,500	------	------
1.0% in 1000 hours	[d]12,000	------	------	11,000	------	------
Transition in 100 hours, psi	16,400	------	------	15,500	------	------
Transition in 1000 hours, psi	11,200	------	------	9,500	------	------
1500° F creep strengths						
0.0001 percent per hour, psi	[d]8,700	------	------	[d]8,100	------	------
0.00001 percent per hour, psi	[d]5,000	------	------	[d]5,500	------	------

[a]Report by R. Franks from Union Carbide and Carbon Research Laboratories, Inc., Oct. 5, 1943.

[b]Report by R. Franks from Union Carbide and Carbon Research Laboratories, Inc., Dec. 8, 1943.

[c]Reynolds, E. E., Freeman, J. W. White, A. E.: The Effect of Chemical Composition Modifications on the High Temperature Properties of 19-9 DL, N155 and Low-Carbon N155 Alloys. University of Michigan Report No. 16, Jan. 25, 1945.

[d]Estimated.

TABLE X

COMPARATIVE PROPERTIES FOR LARGE FORGED DISCS OF

LOW-CARBON N155 AND 19-9 DL ALLOYS

Alloy	Low-Carbon N155	19-9 DL[a]
Heat number	A-11534	B-10429
Chemical composition, percent		
C	0.15	0.33
Mn	1.74	1.44
Si	.37	.65
Cr	21.66	19.10
Ni	19.40	9.05
Co	19.02	----------
Mo	2.76	1.35
W	1.90	1.14
Cb	.79	.35
Ti	----------	.16
N_2	.14	----------
Hot work finishing temperature, °F	1630	1640
Brinell hardness	211-255	202-208
Room-temperature tensile properties		
Tensile strength, psi	118,290	104,700
0.02% offset yield strength, psi	58,750	39,275
0.1% offset yield strength, psi	68,900	50,400
0.2% offset yield strength, psi	72,650	54,700
Elongation, percent in 2 inches	35	30.2
Reduction of area, percent	54	30.7
1200° F tensile properties		
Tensile strength, psi	83,000	57,875
0.2% offset yield strength, psi	49,750	37,900
Elongation, percent in 2 inches	21	34
Reduction of area, percent	33	47.5
1200° F rupture characteristics		
100-hr rupture strength, psi	55,000	40,000
100-hr rupture elongation, % in 1 inch	12	27
1000-hr rupture strength, psi	42,000	34,000
1000-hr rupture elongation, % in 1 inch	10	16
1200° F time-deformation strengths, psi		
0.1% in 10 hours	20,000	16,000
0.1% in 100 hours	17,500	14,000
0.1% in 1000 hours	14,500	12,000
0.2% in 10 hours	31,500	24,000
0.2% in 100 hours	28,000	21,000
0.2% in 1000 hours	24,000	17,000
0.5% in 10 hours	39,500	29,000
0.5% in 100 hours	35,000	26,000
0.5% in 1000 hours	30,000	23,500
1% in 10 hours	45,500	32,500
1% in 100 hours	40,000	29,000
1% in 1000 hours	35,000	26,000
Transition in 100 hours	51,500	39,000
Transition in 1000 hours	39,500	33,000

See footnote at end of table.

TABLE X.- (CONTINUED)

Alloy	Low-Carbon N155	19-9 DL [a]
1200° F creep strengths, psi		
0.00001 percent per hour	15,000	11,000
0.0001 percent per hour	28,000	25,000
1350° F tensile properties		
Tensile strength, psi	60,125	38,100
0.2% offset yield strength, psi	44,500	31,100
Elongation, percent in 2 inches	24	45
Reduction of area, percent	28	69.3
1350° F rupture characteristics		
100-hr rupture strength, psi	31,000	23,000
100-hr rupture elongation, % in 1 inch	15	32
1000-hr rupture strength, psi	24,000	15,500
1000-hr rupture elongation, % in 1 inch	6	24
1350° F time-deformation strengths, psi		
0.1% in 10 hours	13,800	11,000
0.1% in 100 hours	11,000	8,500
0.1% in 1000 hours	8,000	5,000
0.2% in 10 hours	21,400	16,000
0.2% in 100 hours	16,700	12,000
0.2% in 1000 hours	12,000	7,500
0.5% in 10 hours	26,500	21,500
0.5% in 100 hours	22,000	16,000
0.5% in 1000 hours	17,200	11,000
1% in 10 hours	---------------	24,000
1% in 100 hours	25,000	18,500
1% in 1000 hours	19,500	12,500
Transition in 100 hours	24,000	-------------
Transition in 1000 hours	18,000	8,000
1350° F creep strengths, psi		
0.00001 percent per hour	7,900	-------------
0.0001 percent per hour	16,000	7,800

[a]19-9 DL data taken from reference 1.

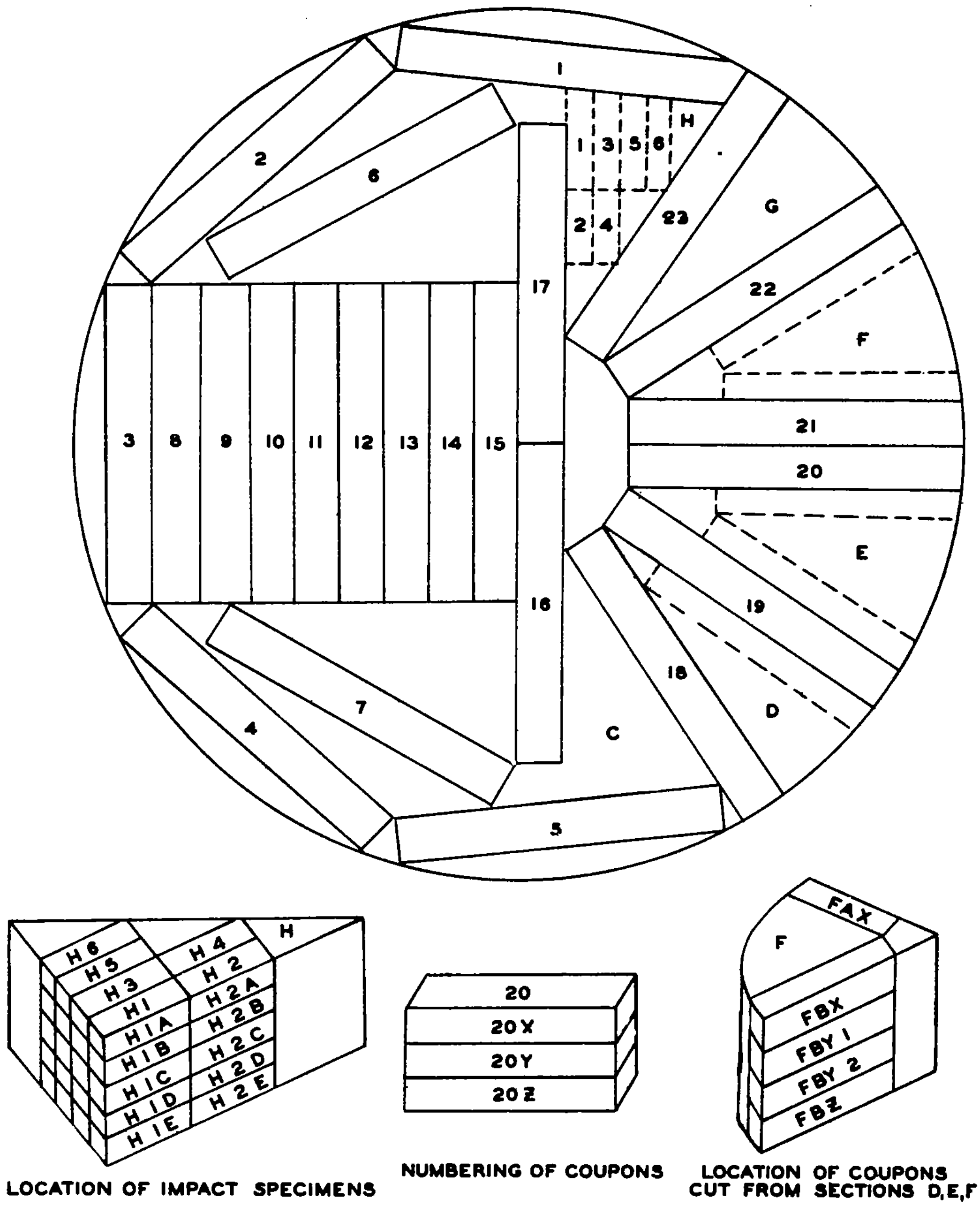


FIGURE 1.– LOCATION OF TEST COUPONS IN LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

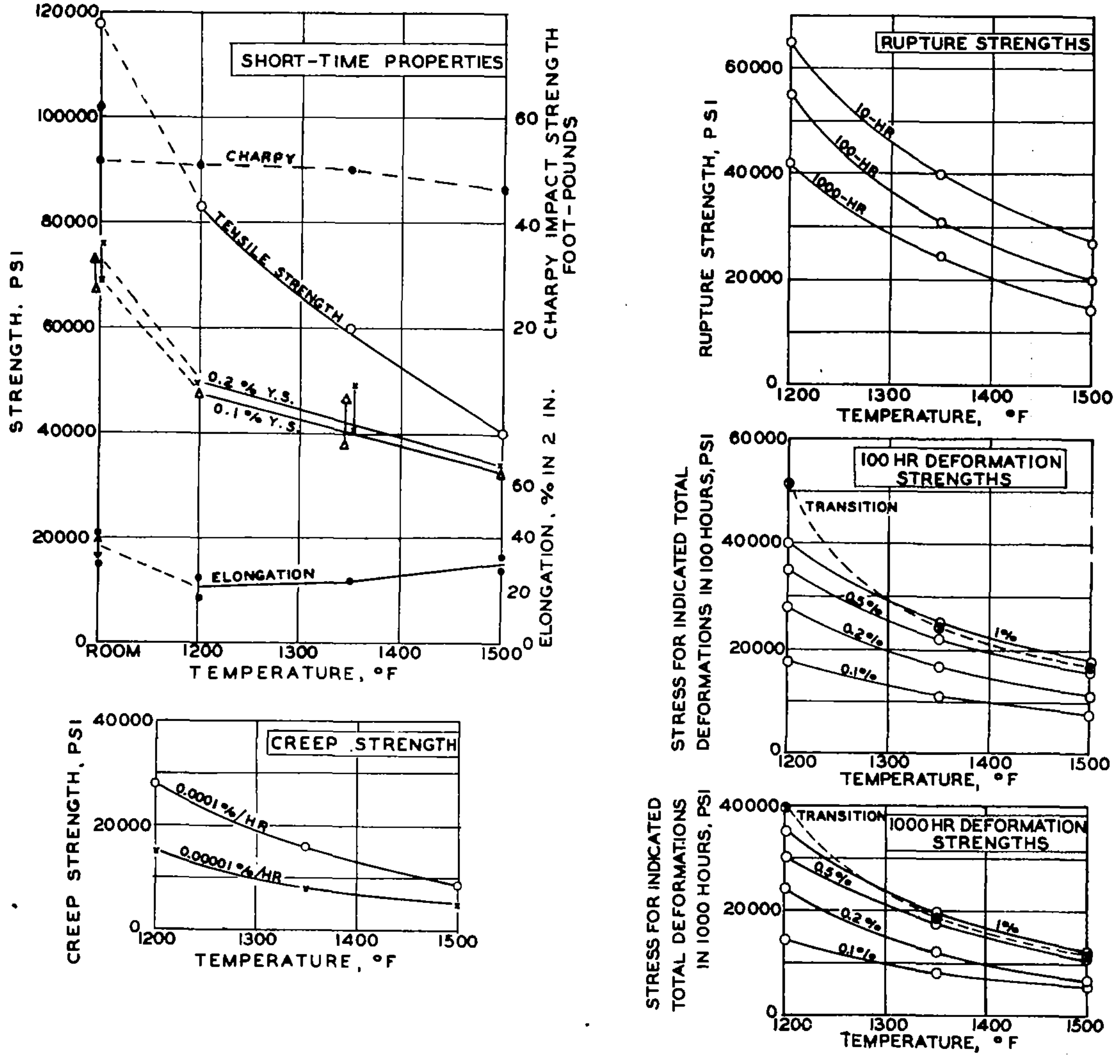


FIGURE 2.- SUMMARY OF THE PROPERTIES OF THE LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

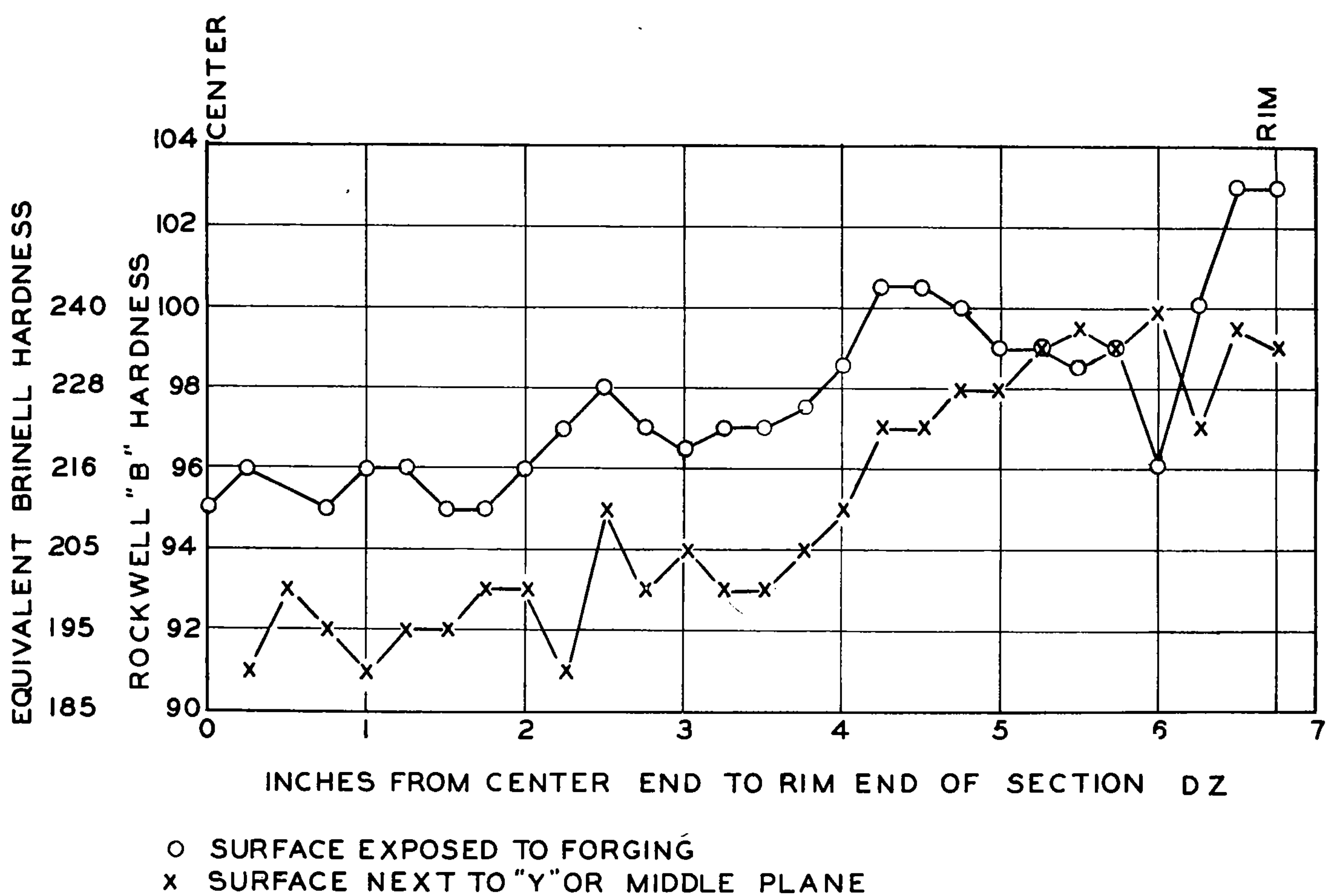


FIGURE 3.- VARIATION IN HARDNESS FROM CENTER TO RIM OF LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

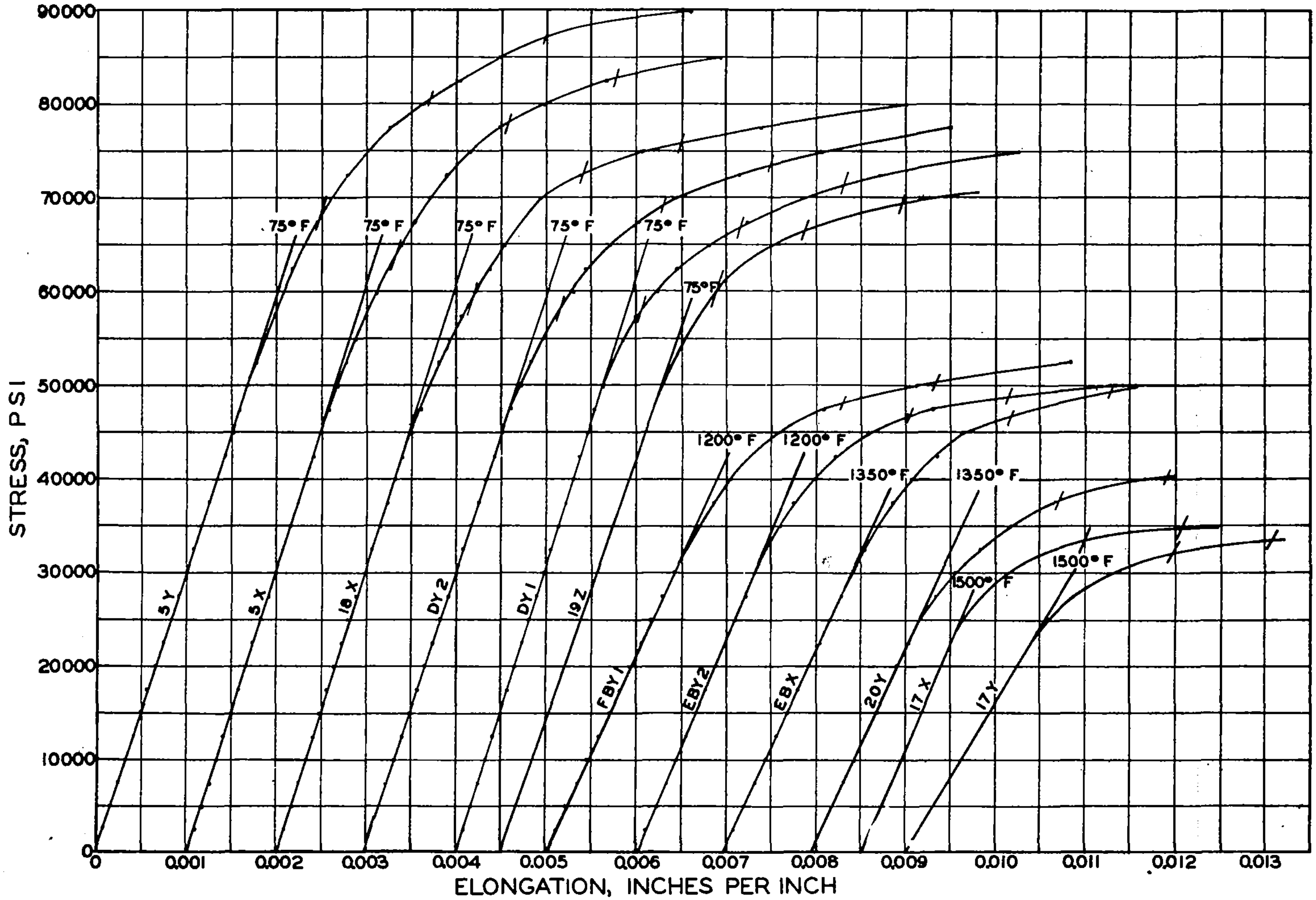
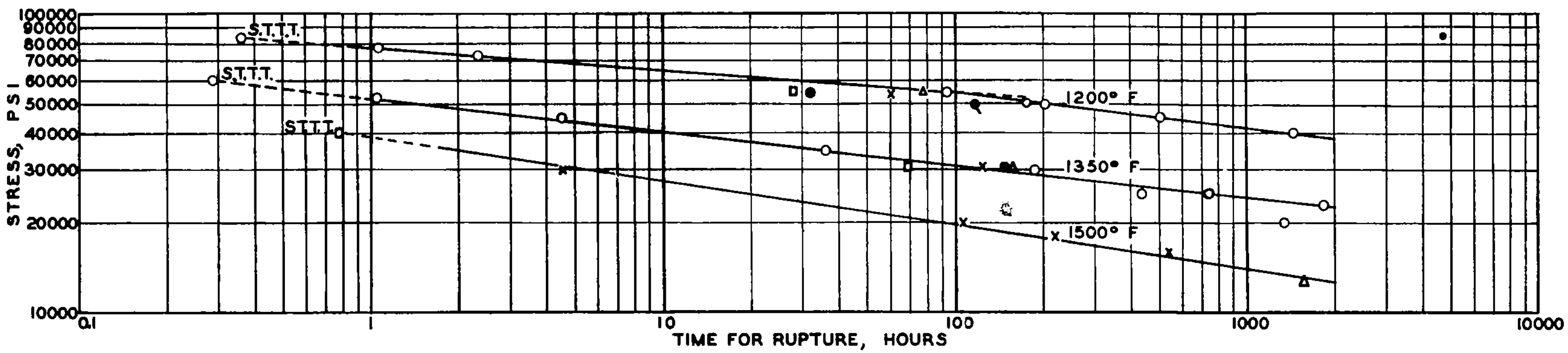


FIGURE 4.- STRESS-STRAIN CURVES FOR SHORT-TIME TENSILE TESTS ON LOW-CARBON N155 ALLOY FORGED DISC NR-66D.



CODE	LOCATION OF SPECIMEN IN DISC
O	CENTER RADIAL SPECIMENS AT RIM
●	SURFACE RADIAL SPECIMENS AT RIM
□	CENTER RADIAL SPECIMENS AT CENTER
x	SURFACE TANGENTIAL SPECIMENS AT RIM
Δ	CENTER TANGENTIAL SPECIMENS AT RIM
●	SECTION C

FIGURE 5.- STRESS-RUPTURE TIME CURVES FOR LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

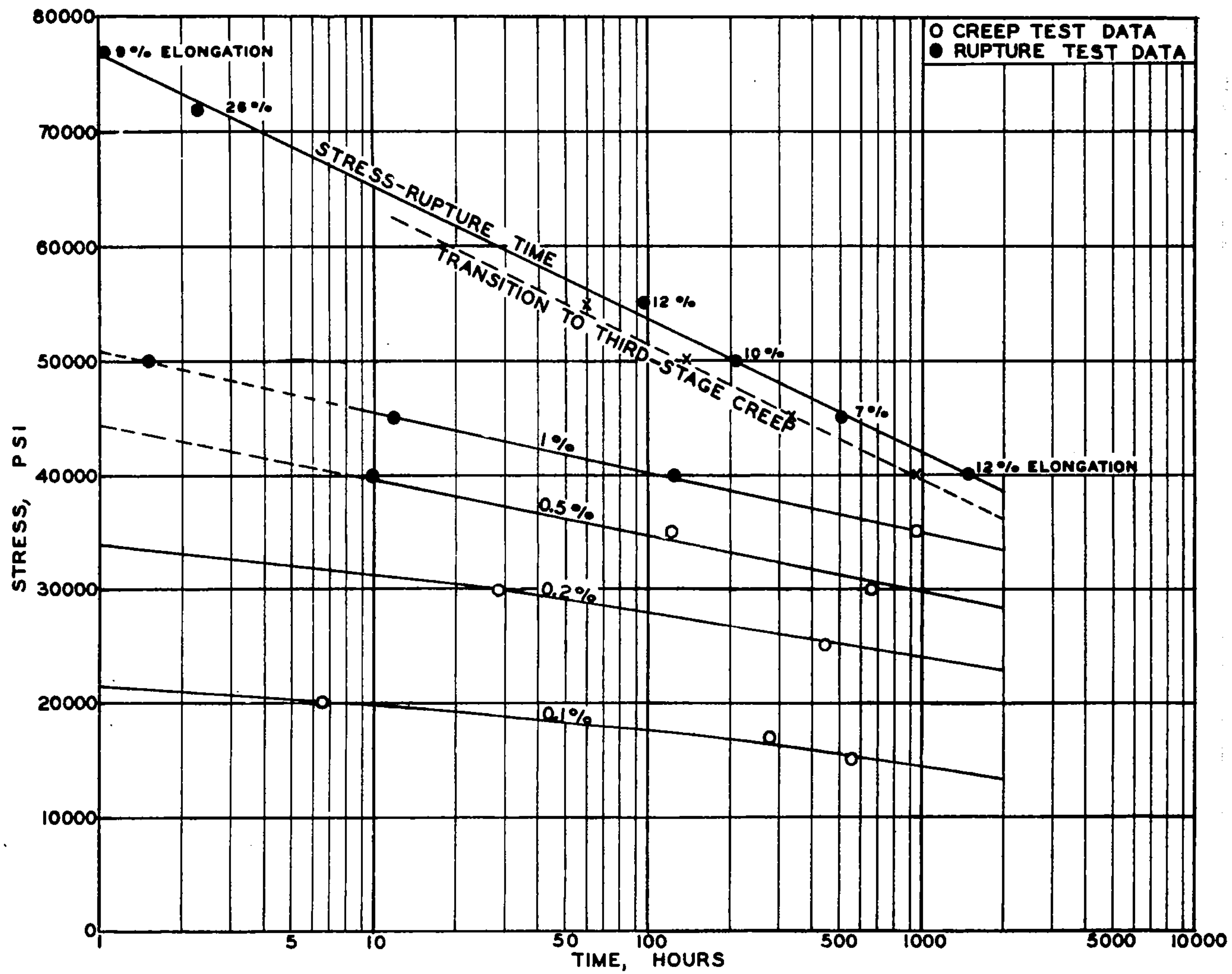


FIGURE 6.- STRESS-TIME FOR TOTAL DEFORMATION CURVES AT 1200° F FOR LOW-CARBON N 155 ALLOY FORGED DISC NR-66D.

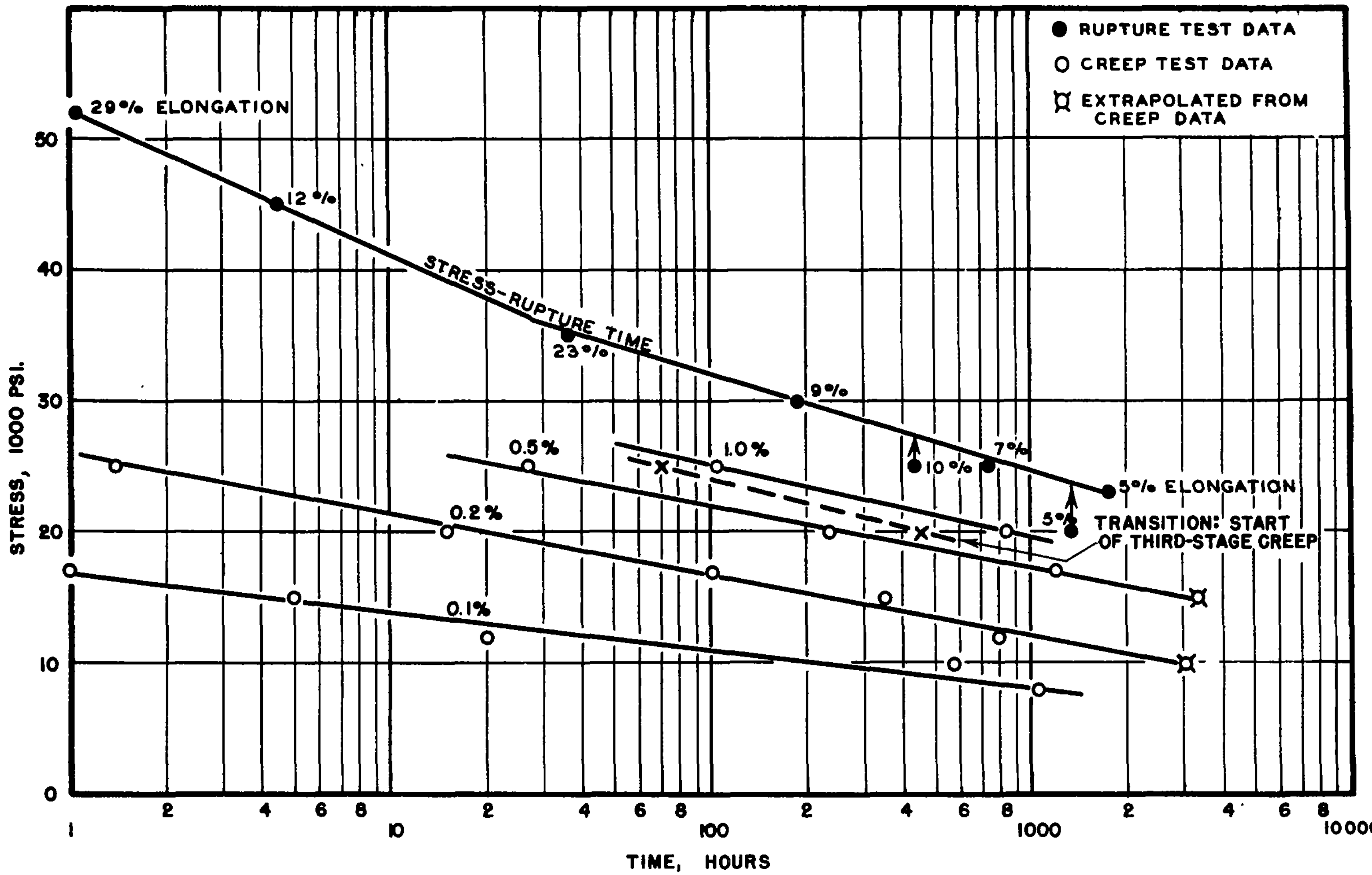


FIGURE 7.- STRESS-TIME FOR TOTAL DEFORMATION CURVES AT 1350° F FOR LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

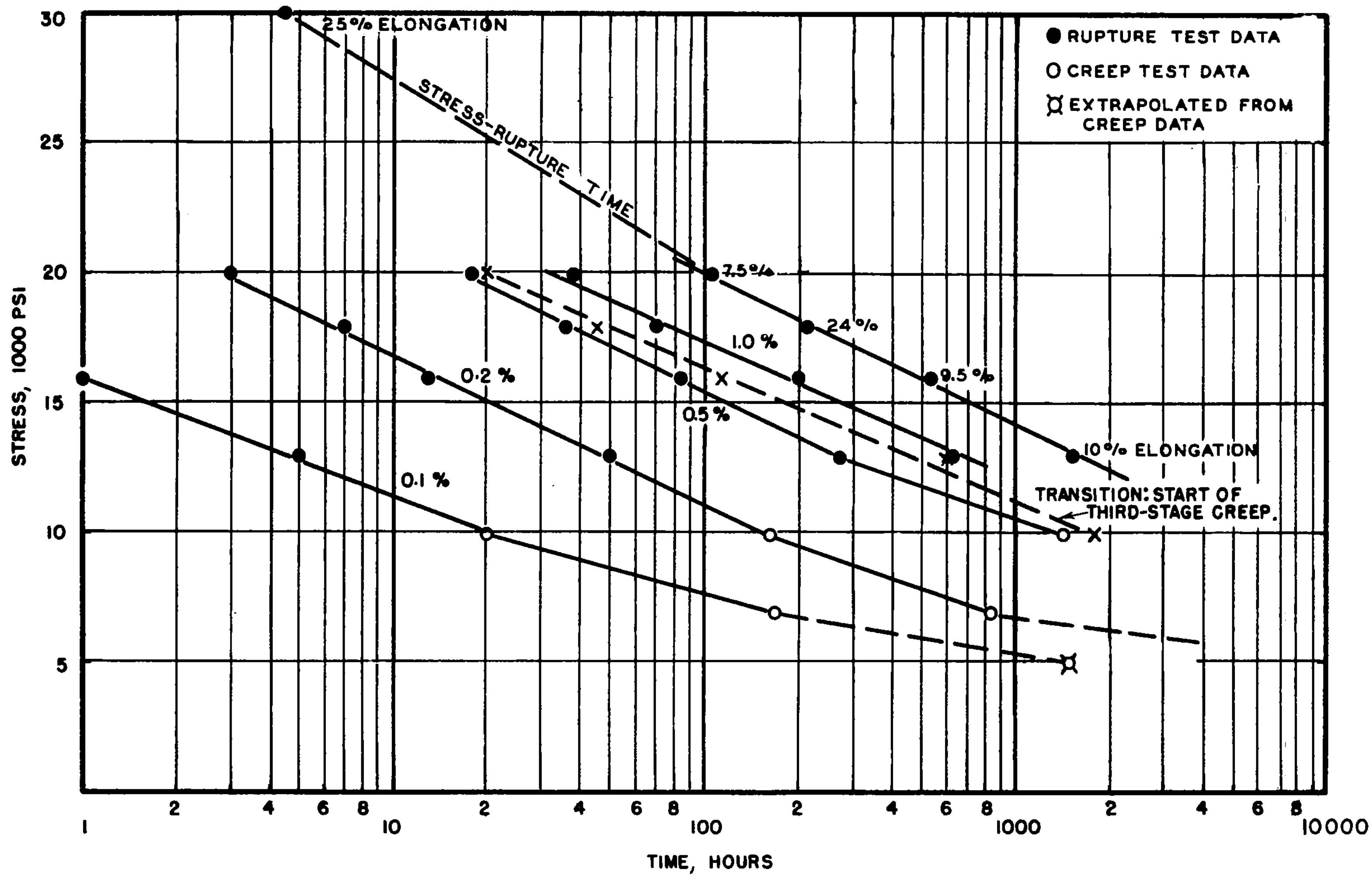


FIGURE 8.- STRESS-TIME FOR TOTAL DEFORMATION CURVES AT 1500° F FOR LOW-CARBON N-155 ALLOY FORGED DISC NR-66D.

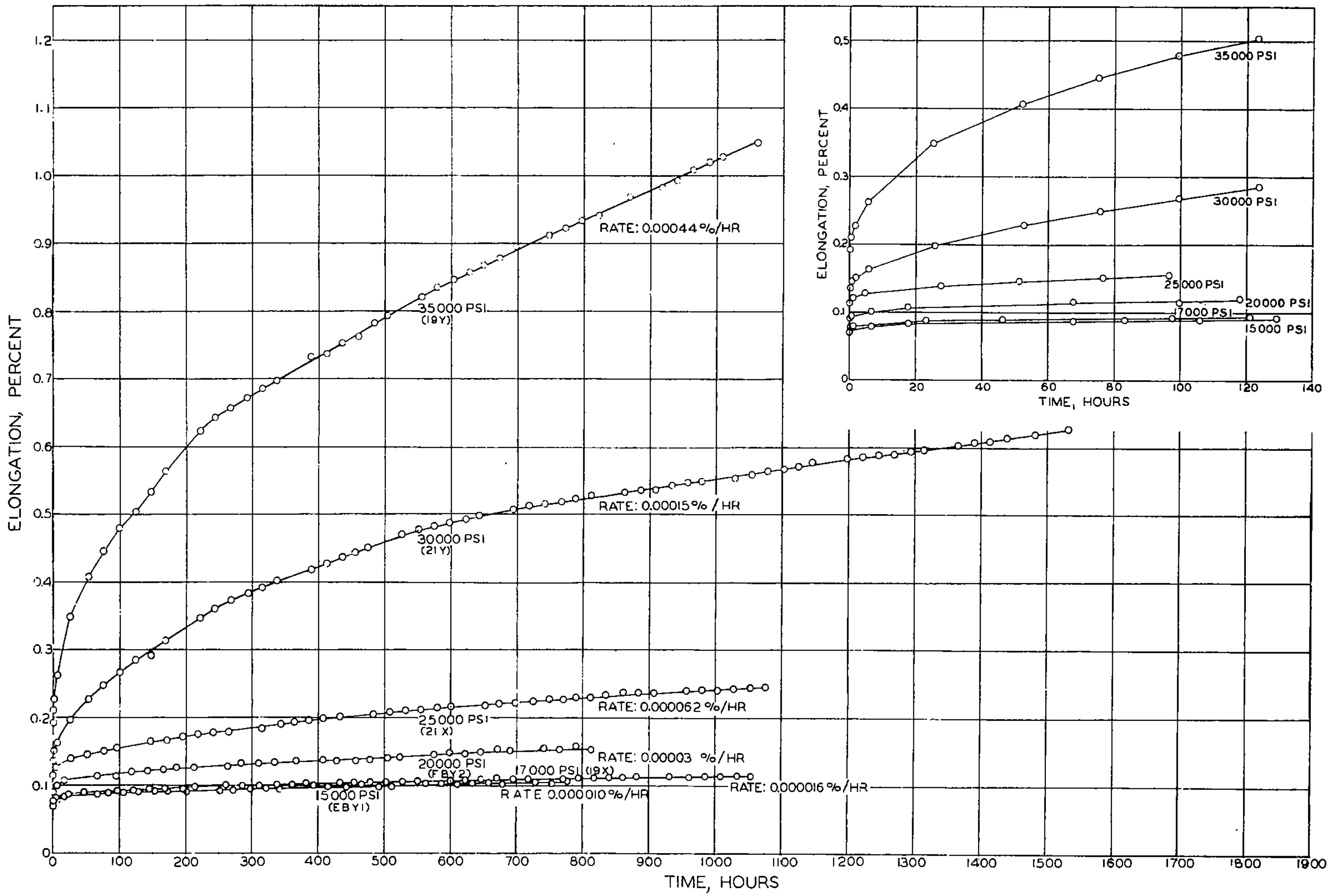


FIGURE 9- TIME-ELONGATION CURVES AT 1200° F FOR LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

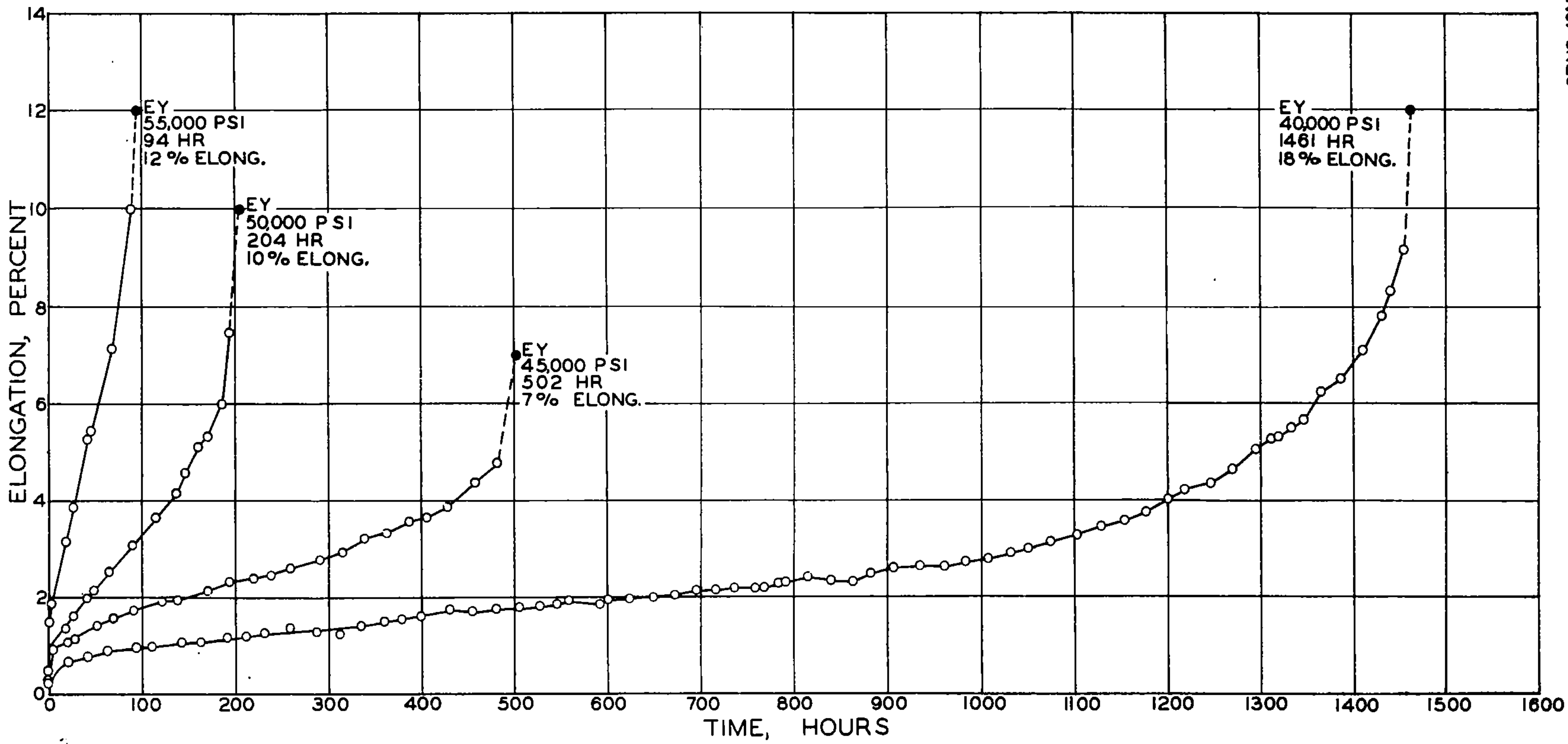


FIGURE 10.- TIME-ELONGATION CURVES FOR THE RUPTURE TESTS AT 1200° F ON LOW-CARBON N 155 ALLOY FORGED DISC NR-66D.

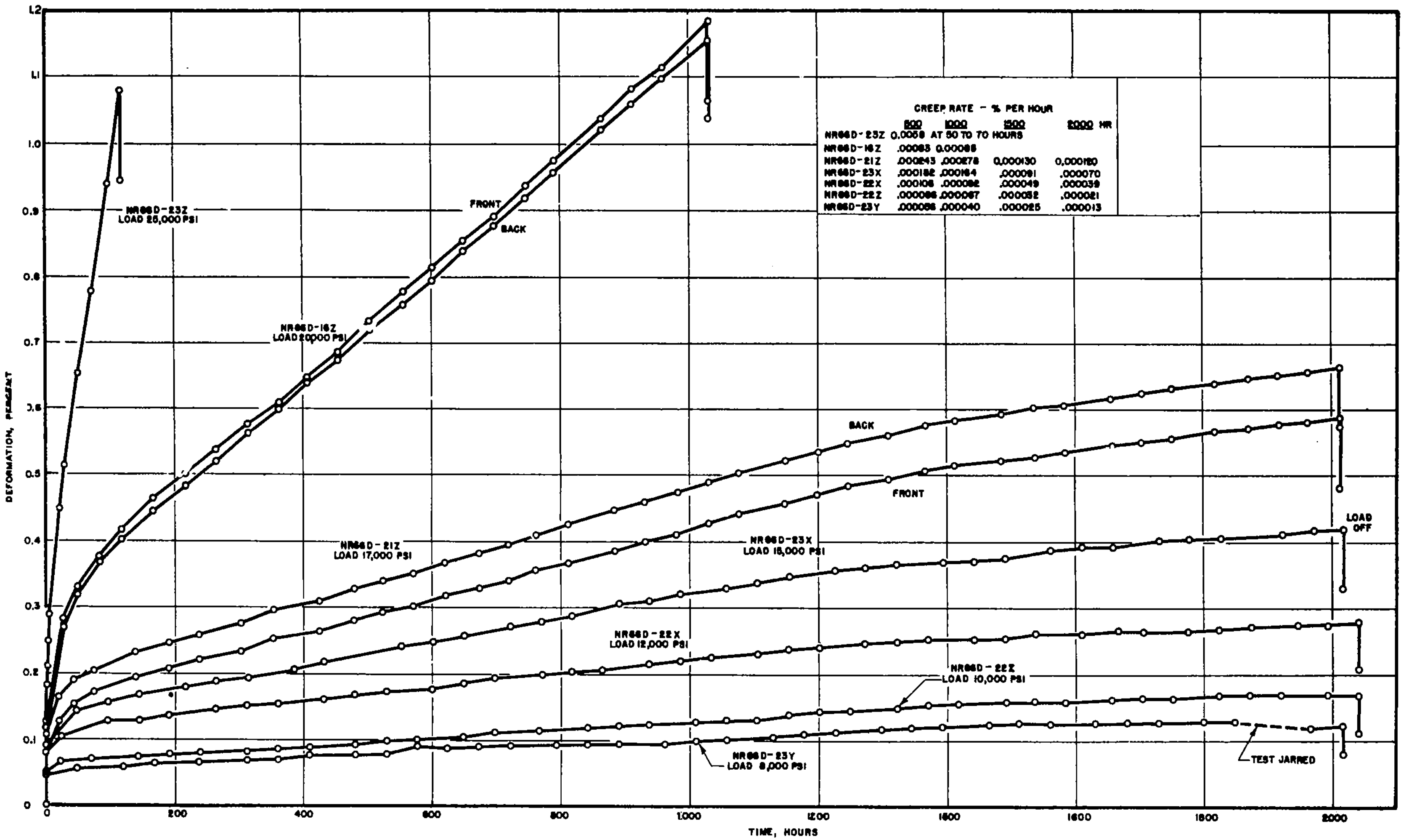


FIGURE 11.- TIME-ELONGATION CURVES AT 1350° F FOR LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

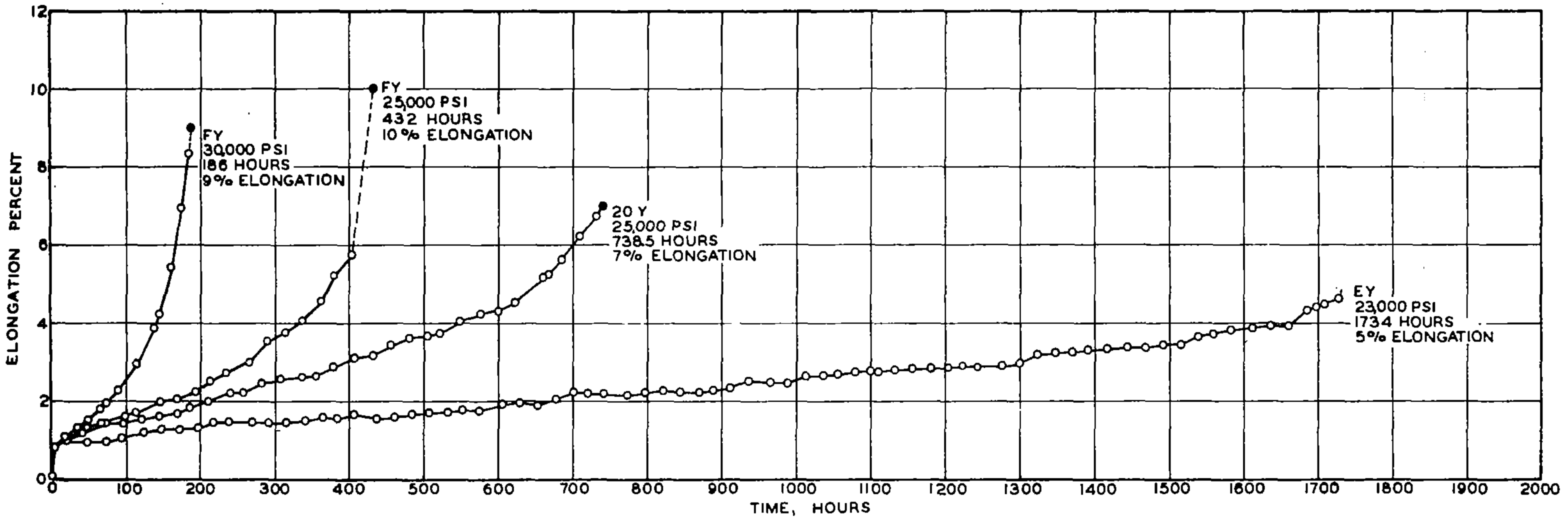


FIGURE 12.- TIME-ELONGATION CURVES FOR RUPTURE TESTS AT 1350° F ON LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

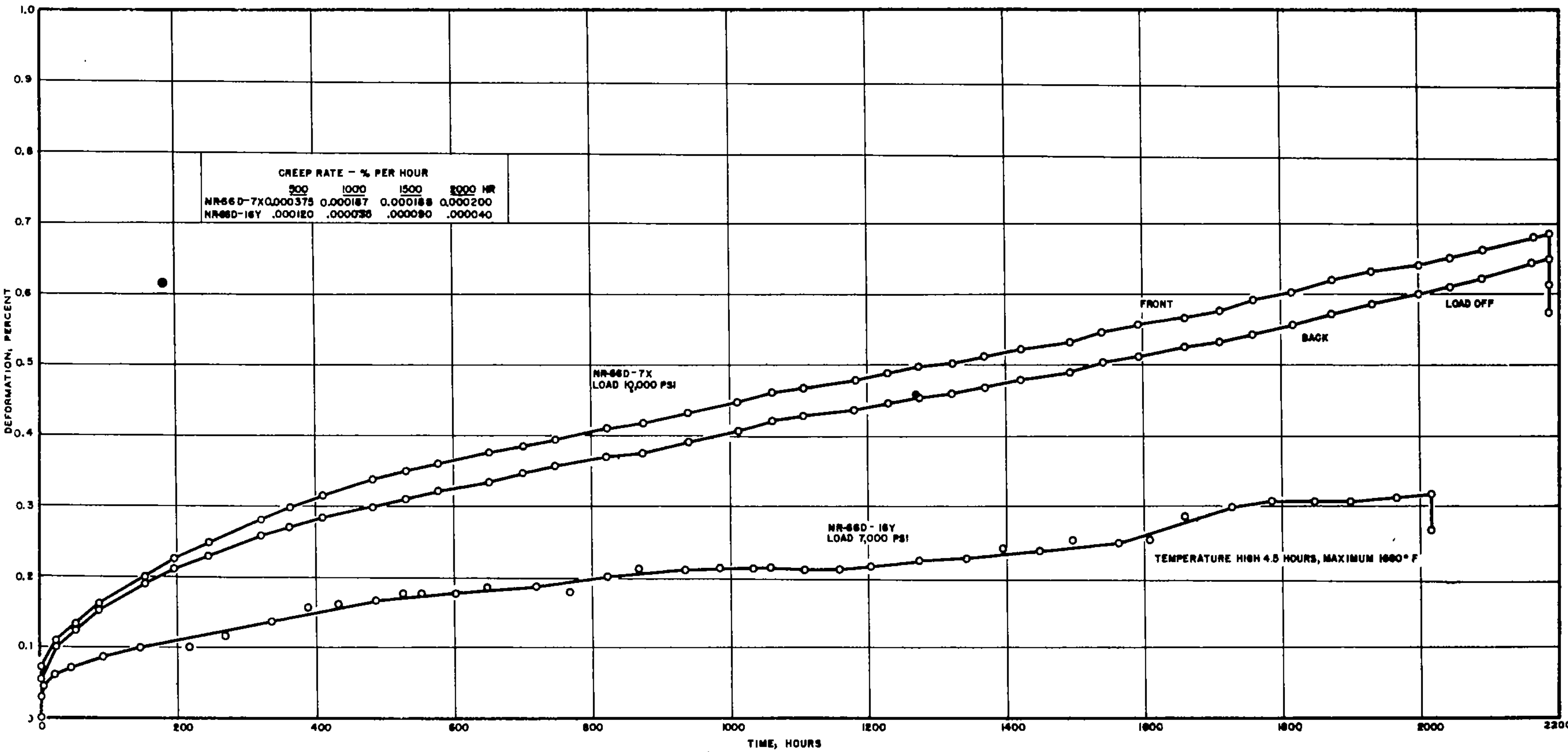


FIGURE 13.- TIME-ELONGATION CURVES AT 1500° F FOR LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

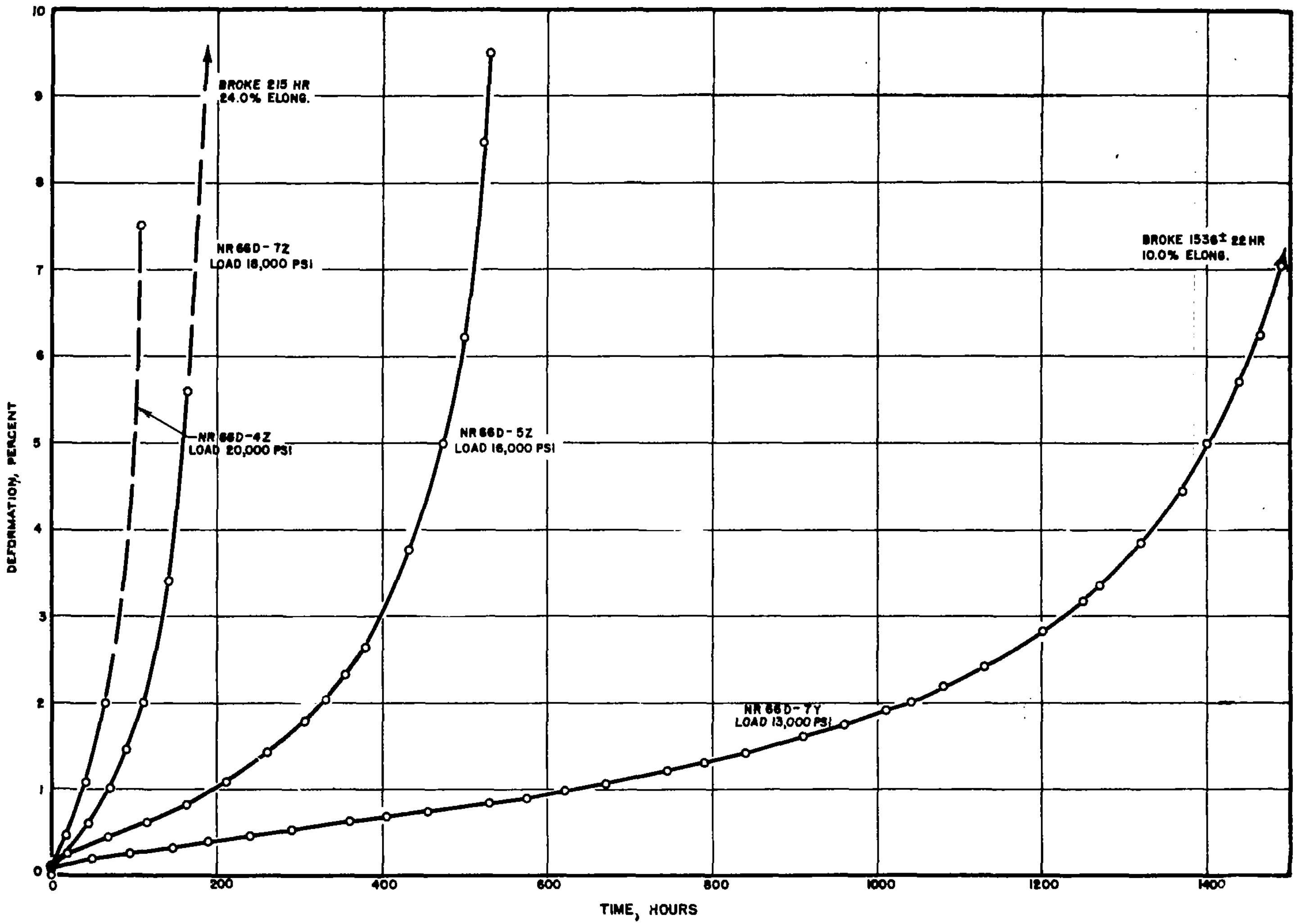


FIGURE 14.- TIME-ELONGATION CURVES FOR RUPTURE TESTS AT 1500° F ON LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

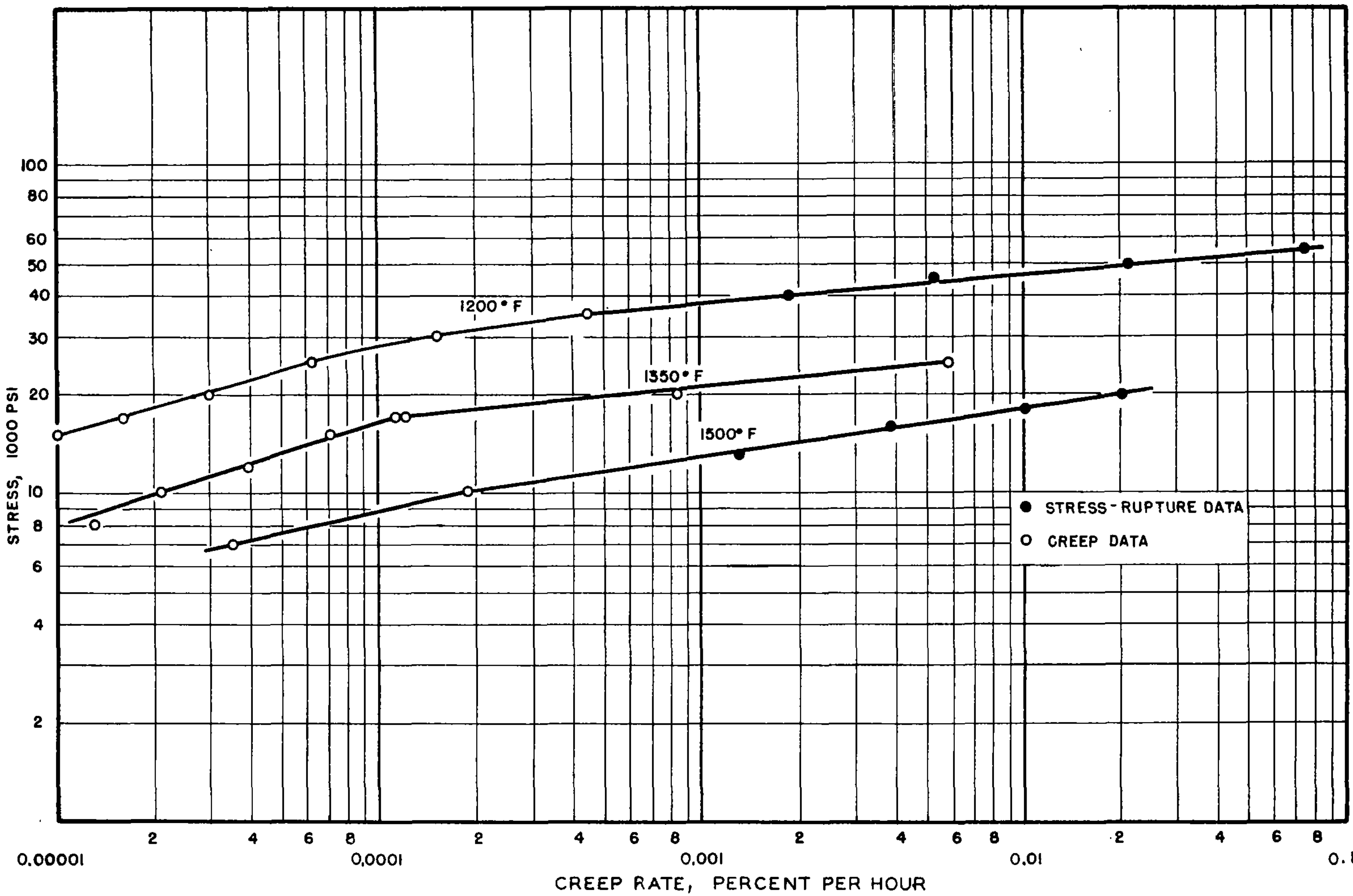
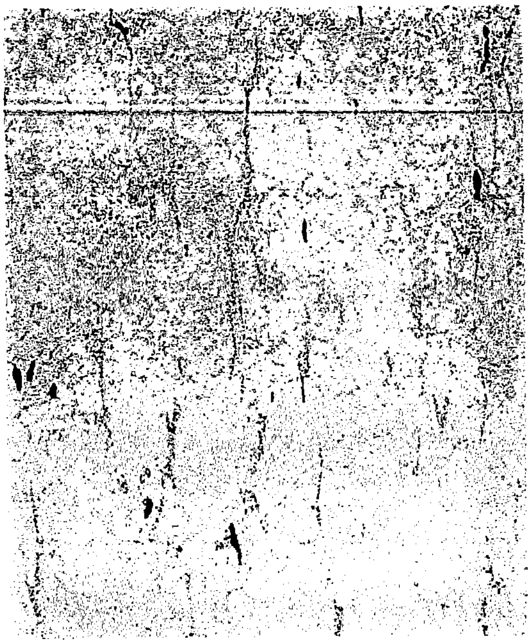
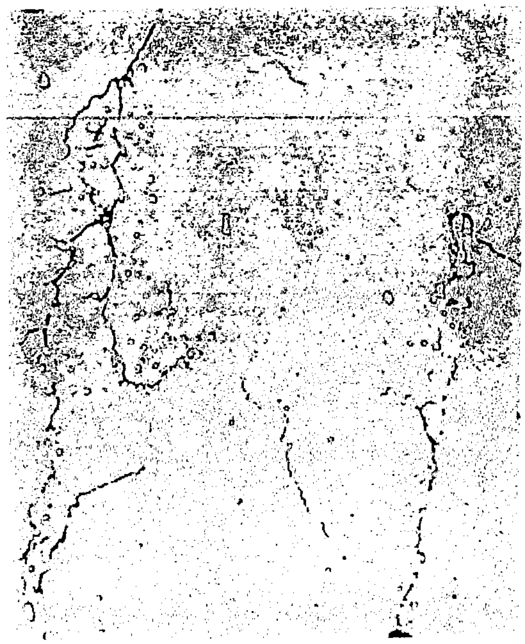


FIGURE 15.- STRESS-CREEP RATE CURVES FOR LOW-CARBON N155 ALLOY FORGED DISC NR-66D.

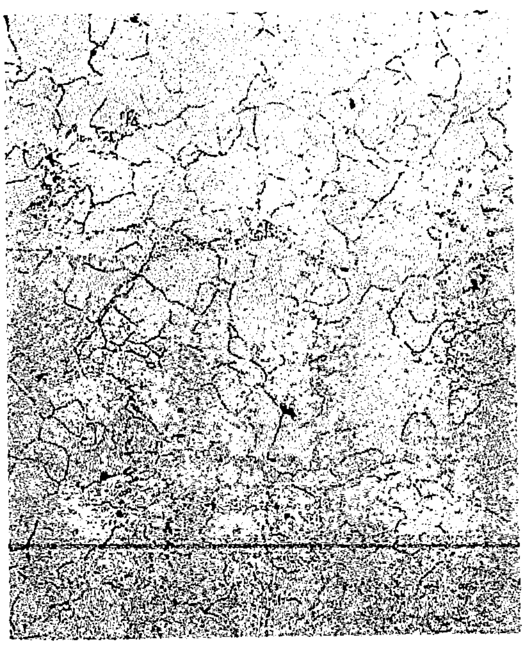


100X

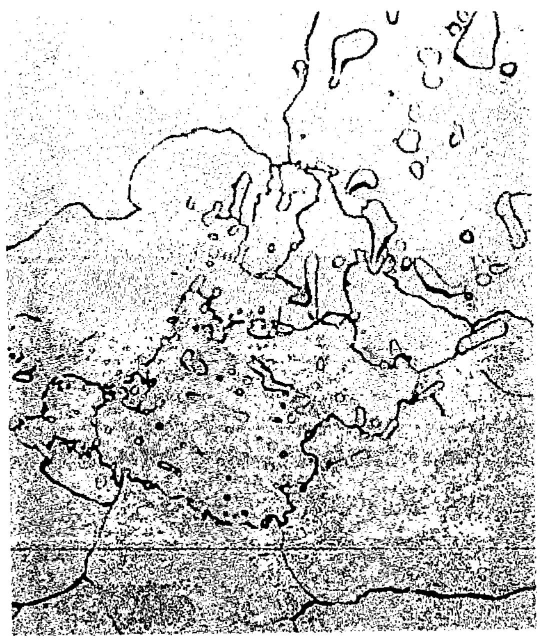


1000X

(a) Specimen 4Y - Radial Section near Rim of Disc.



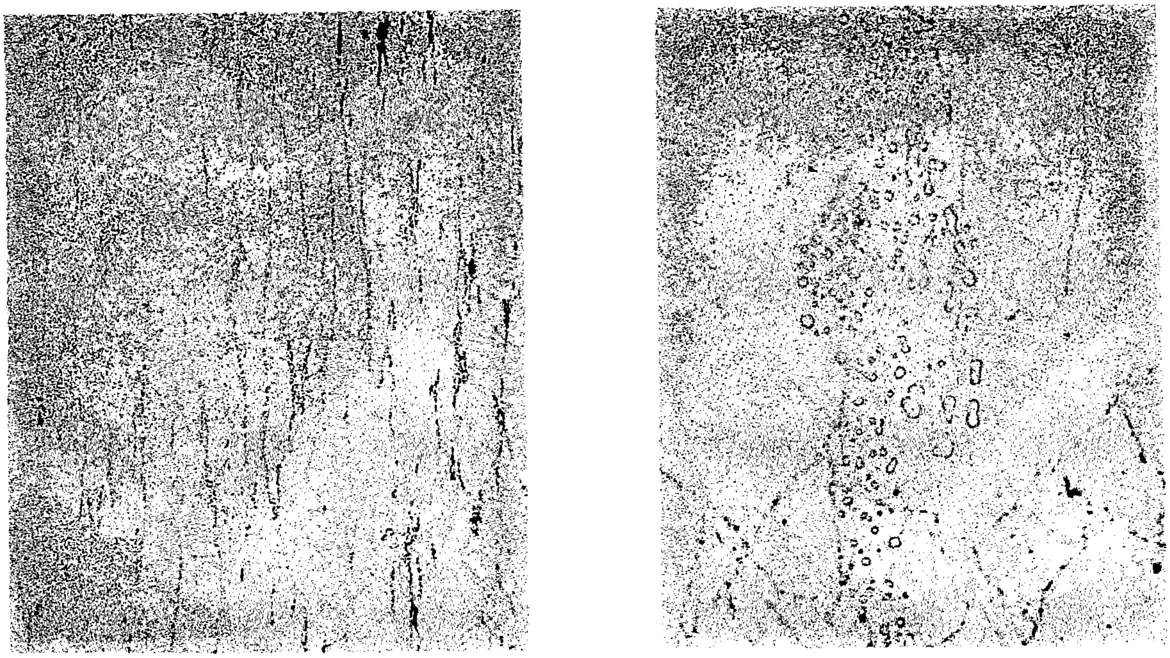
100X



1000X

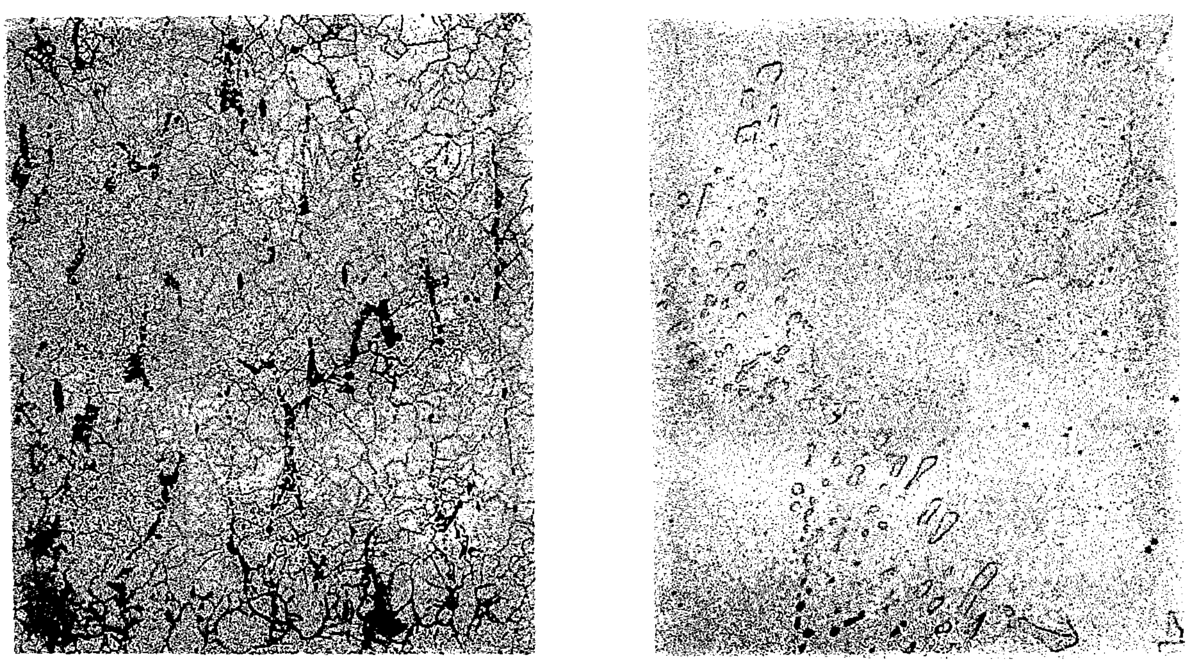
(b) Specimen 21Y - Radial Section near Center of Disc.

FIGURE 16.- ORIGINAL MICROSTRUCTURE OF THE LOW-CARBON N155 ALLOY FORGED DISC.



100X 1000X

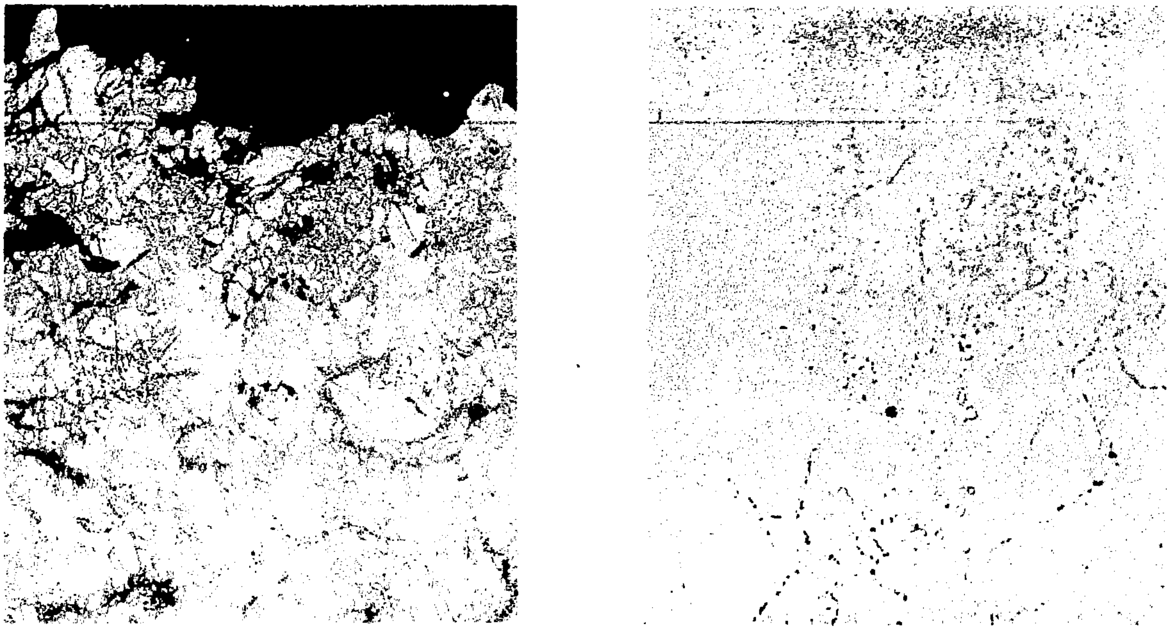
(a) Specimen 21X - 1075 Hours at 1200° F under 25,000 psi.



100X 1000X

(b) Specimen 19Y - 1060 Hours at 1200° F under 35,000 psi.

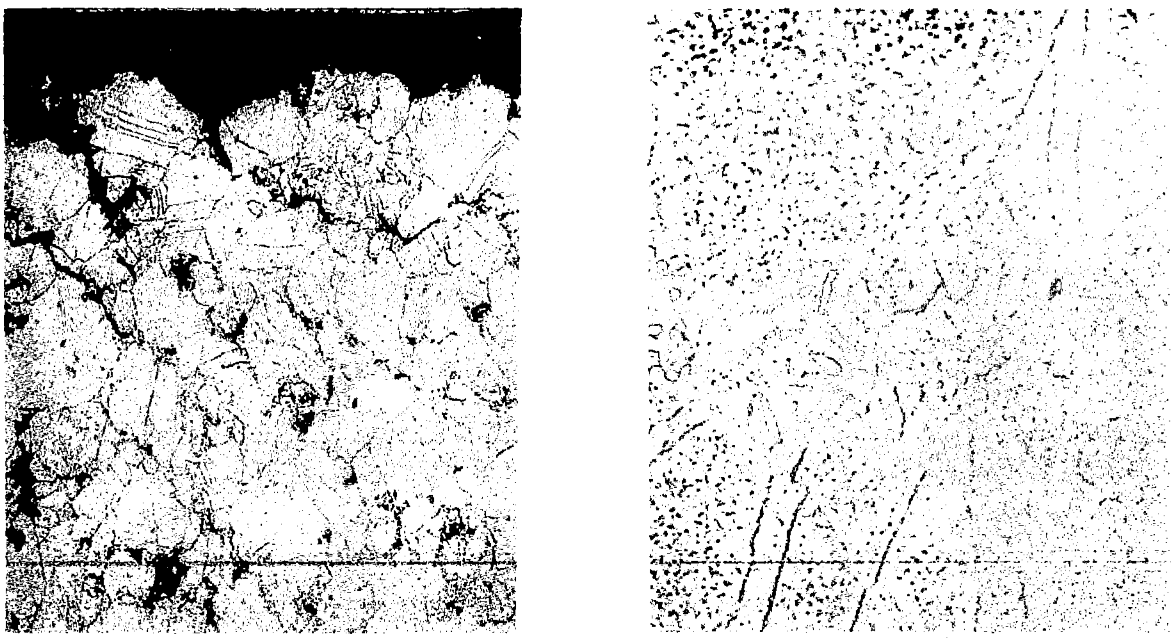
FIGURE 17.- MICROSTRUCTURES OF SPECIMENS AFTER CREEP TESTS AT 1200° F.



Fracture - 100X

Interior - 1000X

(a) Specimen EY - 1461 Hours for Rupture at 1200° F under 40,000 psi.

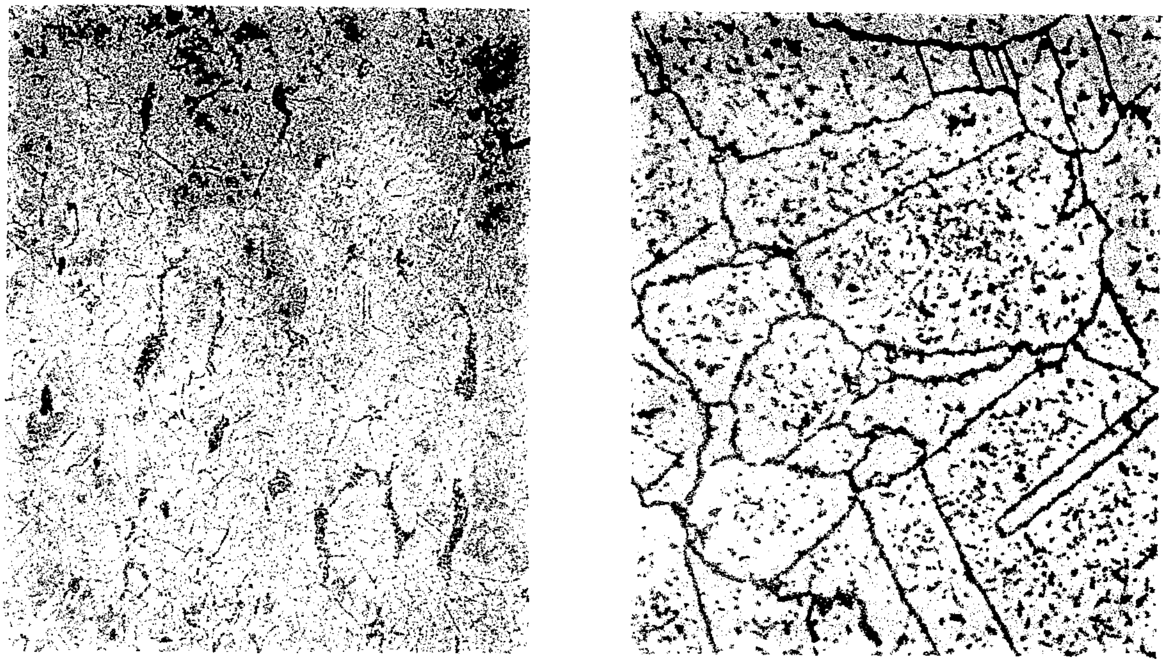


Fracture - 100X

Interior - 1000X

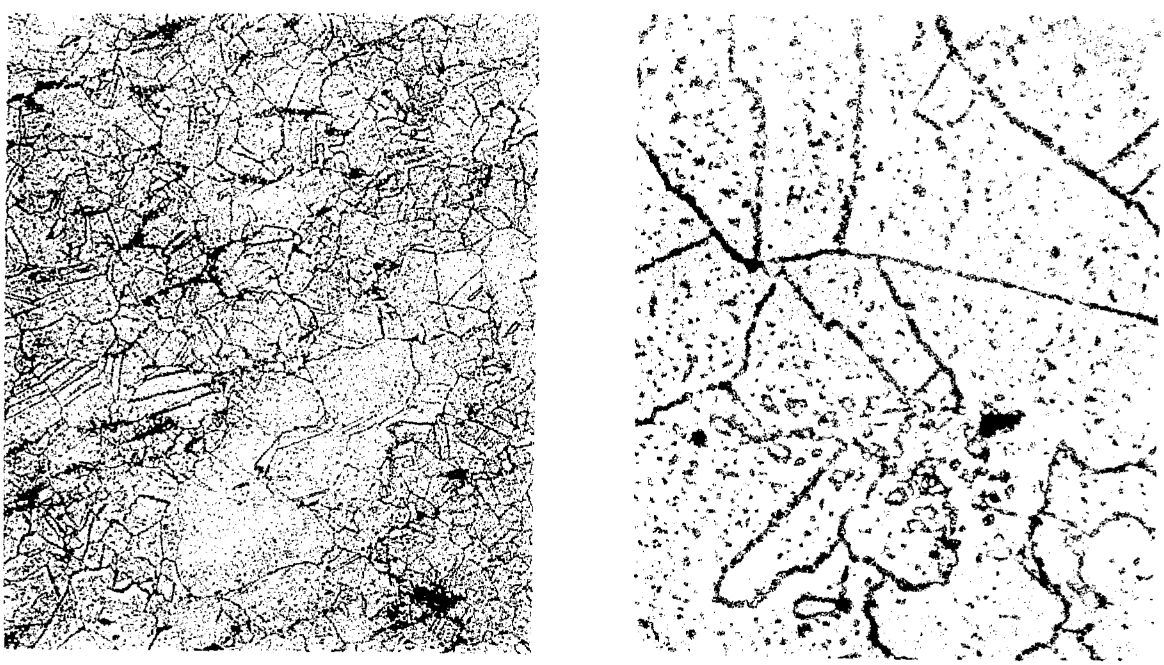
(b) Specimen EY - 1734 Hours for Rupture at 1350° F under 23,000 psi.

FIGURE 18.- MICROSTRUCTURES OF SPECIMENS AFTER RUPTURE TESTS AT 1200° AND 1350° F.



100X 1000X

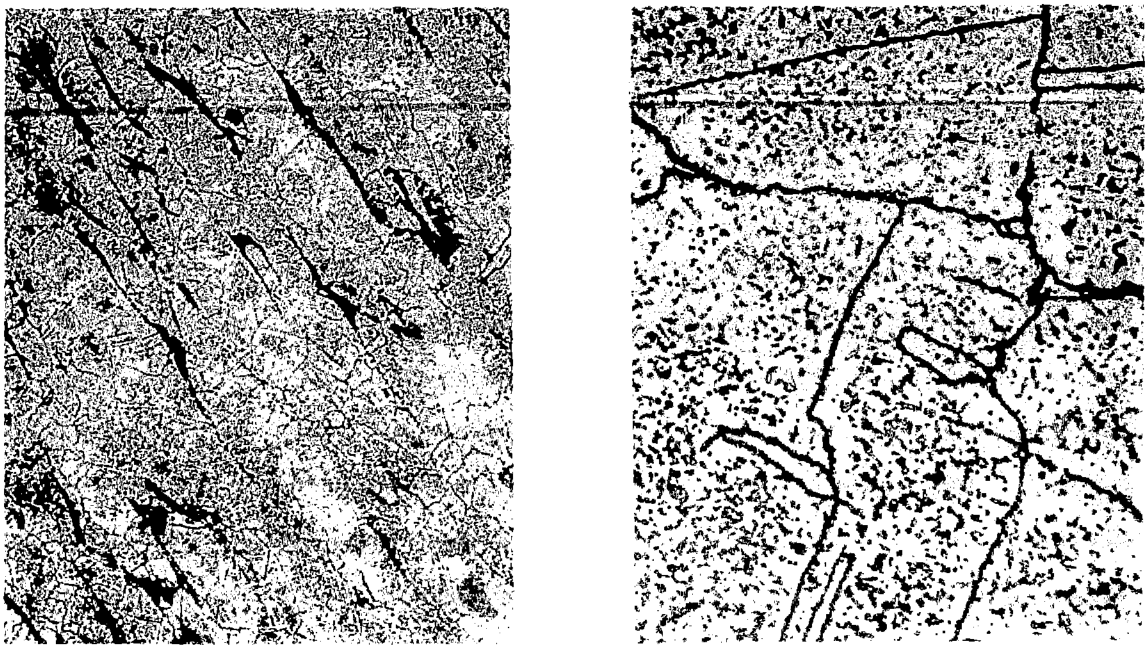
(a) Specimen 22Z - 2040 Hours at 1350° F under 10,000 psi.



100X 1000X

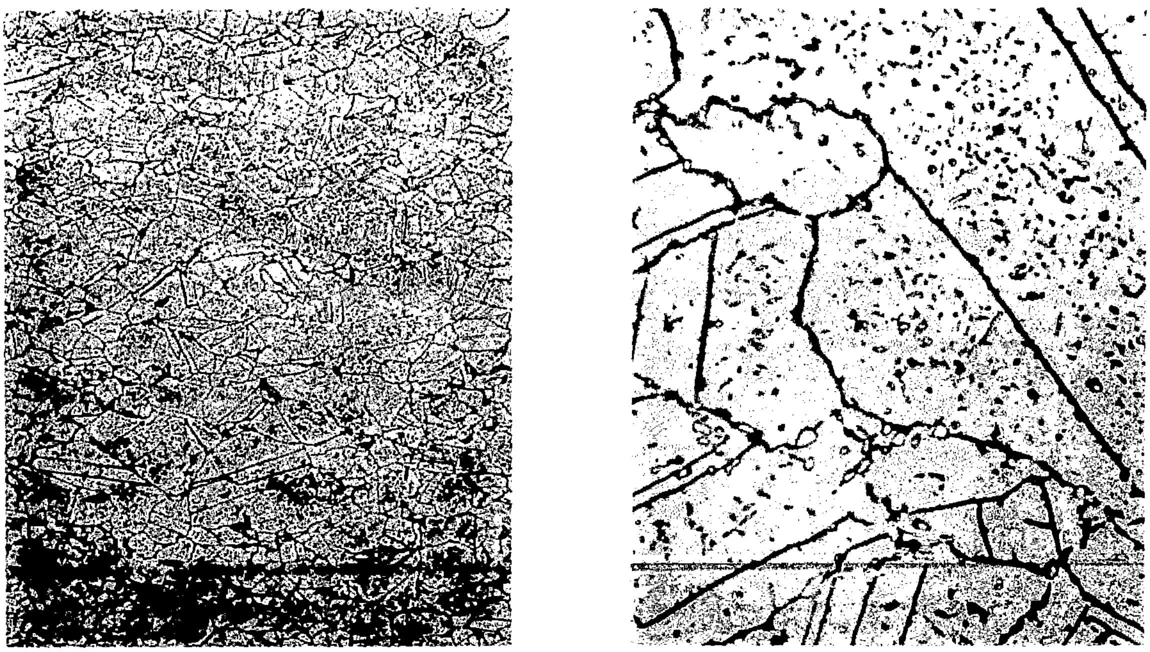
(b) Specimen 23X - 2000+ Hours at 1350° F under 15,000 psi.

FIGURE 19.- MICROSTRUCTURES OF SPECIMENS AFTER CREEP TESTS AT 1350° F.



100X 1000X

(a) Specimen 16Z - 1030 Hours at 1350° F under 20,000 psi.



100X 1000X

(b) Specimen 7X - 2185 Hours at 1500° F under 10,000 psi.

FIGURE 20.- MICROSTRUCTURES OF SPECIMENS AFTER CREEP TESTS AT 1350° AND 1500° F.